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Use of Reprocessed Uranium

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FOREWORD

The subject of the recycling of valuable material is essential for all industries, including the nuclear energy industry. Recent proposals for an 'internationalisation of the nuclear fuel cycle' entail an implicit need for the development of the closed nuclear fuel cycle with efficient use of uranium resources. Continuous attention is being given by the IAEA to the collection, analysis and exchange of information on the back end of the fuel cycle and innovative fuel cycles which are considered complex. The IAEA's role in this area is to provide a forum for exchanging information and to coordinate and encourage closer co-operation among Member States in achieving resolutions of these issues which are of great interest to Member States.

Several countries reprocess their spent nuclear fuel, either in their own facilities or through commercial contracts and possess reprocessed uranium (RepU) in large quantities. Recognizing the importance of this subject, the IAEA has prepared a report aiming to review and summarize the information on the management of RepU.

A working group (WG) was formed to formulate and conduct a technical meeting (TM) on 're-use options for reprocessed uranium'. However, during the preparation of the TM, the WG recognized the necessity to prepare a document in the form of a handbook elaborating technical aspects of the processes involved in the utilization of RepU. It is being published separately as a publication in the Nuclear Energy Series.

The TM was held in Vienna on 29-31 August 2007. The TM was attended by 52 participants from 13 Member States and 2 international organizations viz., IAEA and NEA/OECD. A total of 23 manuscripts were submitted. The TM was conducted in six sessions. They encompassed technical issues such as RepU storage, chemical conversion, re-enrichment, fuel fabrication, transport, in-core fuel management, subsequent reprocessing and disposal options, as well as assessments and comparisons of economic issues and of long-term perspectives.

The IAEA wishes to express its appreciation to all the participants (listed at the end of this document) who contributed to the success of this meeting. The IAEA wishes to express its gratitude to A. Max for his critical review of the proceedings. The IAEA officer responsible for the organization of the TM and for this publication was H.P. Nawada of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

SUMMARY

Recent international initiatives with emphasis on the recycling of nuclear material and a significant rise of the natural uranium (Unat) spot market price have stimulated increased interest in the potential for the use of reprocessed uranium (RepU). In addition, there is a significant interest in IAEA Member States to develop advanced technologies for the recycling of fissile and fertile nuclear materials that would minimize the arising nuclear waste and reduce environmental impacts. Furthermore, the recycling and re-use of potentially valuable nuclear material is important regarding the sustainable development of nuclear energy. However, while several technologies for the recycling of RepU already exist, in some areas experience appears to be still limited and shared knowledge may not be widely available.

As per the suggestion of Technical Working Group on Nuclear Fuel Cycles Options and Spent Fuel Management and to provide a forum for exchanging information as well as to coordinate and encourage closer cooperation among Member States in the area of innovative fuel cycle development a Technical Meeting (TM) on the options for the utilization of RepU was conducted. The TM was held at the IAEA Headquarters in Vienna from 29 to 31 August 2007. It was attended by 48 experts from Belgium, France, Germany, India, Italy, Japan, the Republic of Korea, The Netherlands, Romania, the Russian Federation, Switzerland, the Ukraine, the United Kingdom, OECD/NEA and 4 staff members from IAEA (see the list of participants at the end of this document). Some experts viz., from Canada, France, The Netherlands, the Russian Federation, Spain, the United Kingdom and the USA were not able to participate, due to last minute cancellations. Nonetheless, some of them have sent their presentation materials. The TM provided 23 technical presentations which were classified into 6 categories (see also Content):

1) Management of RepU: Recent analyses of IAEA and OECD;
2) Storage, packaging and transport of RepU;
3) RepU fuel assembly manufacturing;
4) Processing of RepU;
5) Utility experience and potential use; and
6) Economics, market aspects and long-term perspectives of RepU utilization.

According to the titles of the different sessions, the TM discussed technical issues such as RepU storage, purification, conversion, enrichment and re-conversion, fuel fabrication, transport, in-core fuel management, subsequent ERU fuel reprocessing and disposal options. Furthermore, logistic, strategic and economic issues were discussed, assessments and comparisons of different RepU management options were made and long-term perspectives and visions were contemplated.

Thus, this TM complemented in closing the information gap on the current status and future trends in the management of RepU. It identified - to the extent possible - major issues to be considered for future projects, and it supplemented the preparation of the new IAEA-TECDOC on this subject by the IAEA.

1. Session 1: Management of RepU: Recent analyses of the IAEA and OECD

Two papers were presented in the 1st session. While there is currently no shortage in nuclear fuel for the operating and firmly planned reactors, the prudent management of fissile and fertile materials is a key component of sustainable future nuclear energy development which simultaneously addresses efficient use of nuclear materials including repositories and enhancing proliferation resistance. In this context, the recycling and re-use of uranium and plutonium recovered from spent fuel would be the most immediate and pertinent steps in the effective management of nuclear materials.

The first paper [MAX] entitled 'Management of RepU: Recent analyses of IAEA and new approaches towards technical issues' gave a brief overview of the management of RepU in the previous 25 years, focussing on the partly deficient economics for the material's industrial-scale recycling. Until the turn of the last decade, cheap natural uranium was abundantly available due to lower than previously anticipated worldwide nuclear power plant (NPP) growth rates and downblended Russian weapons-grade uranium, thus choking off demand for RepU. But more recent analyses indicate that there is room for RepU in the near- and medium-term uranium supply and demand balance. However, there are bottlenecks in the infrastructure of RepU recycling. Furthermore, the use of RepU entails much paper work, intensified discussions with the regulators and new and/or additional spent fuel storage issues. Investment costs associated with the engineering and licensing of new reactor core designs using ERU fuel may be substantial, and these may still be among the largest obstacles to any short- or medium-term increase in RepU recycling. Nevertheless, when taking a long-term perspective on the fuel supply of light water reactors (LWR), the worldwide dominating reactor concept, it appears that the world is not very rich in cheap uranium resources. Thus, it would not be justified to forget about the fuel supply potentials of RepU. That is why the IAEA - after having prepared a report reviewing and summarizing the information on the management of RepU – stressed the necessity to elaborate more on technical aspects of the processes involved in the utilization of RepU and, therefore, to produce a related new IAEA-TECDOC.

The second paper [BERTEL] entitled 'Management of reprocessed uranium: Main findings from an NEA study' described the highlights of a recent study of the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD) published in 2007[1]. The paper covered various aspects of the storage, processing, re-use and/or eventual disposal of RepU and gave an overview of the amount of RepU accumulated so far in stockpiles. The author emphasized that the worldwide inventories of spent fuel totalling about 200 000 tonnes heavy metal (HM) represent about 190 000 tonnes of natural uranium equivalent. Future arisings of RepU were evaluated taking into account the expected evolutions of nuclear electricity generation and reprocessing capabilities. The alternative options available for the management of RepU were described briefly and their respective advantages and drawbacks were reviewed. Concluding remarks focused on the challenges and opportunities offered by various options for the management of RepU in a sustainable development perspective. The author underlined that RepU management, similar to most steps in the nuclear fuel cycle, raises several technical, industrial and policy issues that may be addressed better through international cooperation than on a purely national basis.

2 Session 2: Storage, packaging, and transport of RepU

The second session focused on the storage and transport of reprocessed uranium. The RepU obtained after the reprocessing operations is uranyl nitrate hexahydrate (UNH) in liquid form. Depending on the timing of recycling, the RepU will be chemically converted into UO_3 or U_3O_8 (solid forms) or UF_6 (a gaseous form). The physical characteristics of the oxide forms are suitable for long-term storage as they are very stable products. What is more, they can easily be transported in commercial containers. The gaseous form UF_6 is also a stable product, but it has propensity to oxidation. It can be stored in standard 30B cylinders which are also amenable for transport. As RepU is coupled with the presence of synthetic nuclides, there is a need for a more considered assessment prior, during and after its transport. Particularly, the decay products of ^{232}U and ^{236}U may cause significant radiological problems. On evacuating the UF_6, the daughters of ^{232}U become concentrated in the heel giving off high radiation levels for many years. Thus, heeled containers require a careful management.

[1] ORGANIZATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, Management of Recyclable Fissile and Fertile Materials, NEA#06107, ISBN: 978-92-64-03255-2, OECD-NEA, Paris, 2007.

The first paper [OWEN] of this session entitled 'Key aspects of transporting reprocessed UF6' highlighted the important features in transporting RepU. The paper dwelled on the consideration and comparison of some of the key aspects and differences associated with transporting reprocessed feed and ERU in the form of UF6. The four key methods of IAEA regulatory control which applies to the transport of UF6 were described, thereby comparing the differences in how these requirements apply to virgin and reprocessed UF6. Regarding the consequences resulting from the presence of the synthetic radionuclides found in RepU, the importance of 'timing' was addressed, both through the processing stages such as conversion, enrichment, re-conversion, fuel fabrication and during transport. The paper considered the expected waste generation at all the above facilities and how it might be minimized or dealt with. In this context the paper identified and discussed problems resulting from the reprocessed cylinder heel, its transport requirements and limitations. The paper also directly compared the ASTM Specifications C787 and C996 with the IAEA transport regulations, identifying how well they interface. It also described how IAEA transport package requirements can be influenced by the chemical form of the material, for example, the package type differences of reprocessed UO2 versus reprocessed UF6 at the same specification.

The second paper [FLYNN] in this session dealt with 'Cost effective transport of industrial fissile packages by sea'. Sellafield Limited provides a storage service to its customers for uranium products in the form of UO_3. As this service is not indefinite, at some point the UO_3 requires exporting. The UO_3 to be exported has a range of ^{235}U enrichments some of which meet the IAEA Fissile Excepted Package criteria and some of which are marginally outside this criterion. Therefore, this implies that two package types will be required: a Fissile Excepted package and a Fissile package. The latter package will require approval by the Competent Authority. The challenge is to minimise the number of shipments by optimising a single package design and the loading arrangement of this design to enable the safe transportation of large volumes of the fissile UO_3 material. To accommodate the higher enriched material the use of an Industrial Fissile (IF) Package was proposed. IF Packages are typically IP-2 qualified packages supported by a criticality safety case. This safety case demonstrated an adequate sub-critical safety margin, without claiming any integrity for the packaging under accident conditions of transport. This option provides the potential for significant cost savings, particularly with respect to package testing, as the safety of the package needs only be demonstrated for normal conditions of transport.

3. Session 3: RepU fuel assembly manufacturing

Two papers were presented in the third session, one from Russian authors and one from a French expert. According to these papers, from the applied techniques' point of view there are very little – if any – differences between the manufacturing processes for ERU and ENU fuel. Likewise, containers may be licensed for both the transport of ERU and ENU fuel assemblies. However, there is a clear separation of the flow of ERU and ENU fuel inside the fabrication plants, with special radiation protection features regarding the processing of RepU. This separation applies to the re-conversion of the UF_6 into UO2 powder, the pelletizing, the rod and assembly manufacturing and – most importantly – to the management of the emptied UF_6 containers. A central theme of this Session as well as of several others of the TM was the recognition that - given the increase of the RepU's γ dose rate over time - the reduction of lead times in ERU processing steps is of paramount importance.

The first paper [PIMENOV, et al.] described 'Manufacture and operational experience of reprocessed uranium in WWER reactors'. The authors underlined that the long-term operation of nuclear power reactors and the further increase of installed nuclear generating capacities contemplate the closure of the nuclear fuel cycle with the recycling of plutonium and of RepU (in Russian Federation also referred to as 'uranium reclaim'). Since about 20 years, RepU gained in Russian Federation from the reprocessing of spent fuel from WWER-440, BN-600, research and transport reactors is used for the fabrication of fuel for RBMK reactors. However, more recently the usage of ERU fuel has been

implemented in WWER-440 (Kola-2) and WWER-1000 (Kalinin-2) reactors. Given the existence of ^{234}U and ^{236}U in RepU, the paper described the authors' approach to quantify the compensation of these even uranium isotopes (primarily ^{236}U in the content range from 0.11 to 1.0%) with respect to ERU fuel with an equivalent enrichment between 3.3 and 4.6% ^{235}U, and the paper discussed the results. The paper concluded with an overview of the ERU fuel operating experience in Kola-2 and Kalinin-2 which was in line with calculated data and did not show any fuel failure.

The second paper [ROMARY] dealt with 'The ERU fuel manufacturing at AREVA NP'. Within the Fuel Manufacturing Business Unit (FMBU) of the AREVA NP Fuel Sector, the FBFC Romans fuel plant has acquired a long standing experience in the fabrication of ERU fuel assemblies. Since the first ERU manufacturing campaign took place at Romans in 1987 on behalf of Electricite de France (EDF), more than 400 tonnes ERU fuel assemblies were produced. Romans is currently licensed to manufacture 150 tonnes ERU fuel per year on the basis of a specification included into the general technical instructions of the plant with especially a maximal ^{232}U content of 15 ppb. The paper stated that the external exposure is mainly due to the ^{232}U decay products, that the γ emission from ERU is 10% higher than from enriched natural uranium (ENU), that the contribution of neutrons to the external exposure is very low and that the γ dose rate level increases with time. Considering all these facts, the main management principles were defined regarding the internal and external exposure of the manufacturing personnel through all the manufacturing steps (UF_6 re-conversion, pelletizing, rod and fuel assembly manufacturing). These principles comprise the reduction of the lead time of the ERU material in the whole facility, the regular control of the material storage areas, the identification and inspection of the places where the material can be accumulated, the control of the full UF_6 cylinders as well as of the empty UF_6 cylinders by knowing that the ^{232}U decay products remain in the cylinder during the UF_6 evaporation, the loading of the ERU fuel assemblies in the containers immediately after their manufacturing, and the storage of loaded assembly containers at the rear of the storage room with a specific labelling in a restricted access area. The authors underlined the important fact that the Romans fuel plant is being renewed to be able by the end of 2008 to manufacture both ENU and ERU fuel. After that renewal all the equipments will comply with the most stringent standards regarding safety and environmental protection and will achieve the highest quality and productivity level.

4. Session 4: Processing of RepU

There were five presentations on various aspects of the processing of RepU. Different processing options for RepU were described, such as its physical enrichment of ^{235}U and its enrichment by blending. In addition, technical steps, such as UF_6 purification by means of UF_6 transfer from one cylinder to another one, by radiochemical separation and by purification cascades were discussed, and so were also the conversion of RepU, re-conversion, and fuel fabrication. The papers underlined that sophisticated technical concepts for the industrial-scale processing of RepU into ERU fuel have been developed successfully, but that their implementation will depend on one precondition: the potential customers' decision to recycle significant RepU quantities on a long-term basis.

The first paper [GRIMOLDBY, et al.] of this session dealt with 'Reprocessed uranium experience and UK options for the NDA and Springfields Fuels Limited'. In April 2005, the Nuclear Decommissioning Authority (NDA) has taken the strategic responsibility for the UK's nuclear legacy. As part of its strategic commitment, NDA carried out an evaluation of the potential liability or asset of the UK's stocks of civil separated uranium (including RepU) and plutonium. The NDA Strategy, published in March 2006, identified three bounding scenarios for the disposition of its stocks of nuclear material which encompass all other potential options. These are the materials' declaration as waste, its storage pending a decision to use or declare it as waste and its use by recycling to the optimum possible extent. According to the Study, a decision on the way forward will depend on an assessment of the future price projections and demand for uranium. If the third scenario (use) would

apply, material with a reasonable prospect of being recycled would be differentiated from other material which would be designated as waste and disposed of. RepU would be recycled as fuel into pressurized water reactors (PWR), acknowledging that other reactor types could be considered as well. The available RepU stocks would be sufficient to fuel up to two PWRs of 1000 MWe each over their 60 year lifetime. To develop and implement this recycling route significant investment for a number of RepU processing facilities would be required. However, the costs associated with this scenario would be offset by the worth of the RepU being recycled.

The second paper [KOROTKEVICH, et al.] was entitled 'Reprocessed uranium handling at the Siberian Group of Chemical Enterprises (SGChE)'. The SGChE production is shipped into both Russian Federation's market and the international market. At the international market of services for uranium enrichment the SGChE has been since 1993. The experience of processing RepU at SGChE includes the following activities: the purification at the Radiochemical Plant of spent slightly irradiated fuel from two commercial reactors operated by SGChE and also RepU from power reactors, the conversion of uranium with up to 1% ^{235}U into hexafluoride at the Conversion Plant, and the enrichment of uranium hexafluoride with up to 5% ^{235}U using the gas centrifuge equipment of the Enrichment Plant. In 1992, the SGChE started the commercial-scale conversion and enrichment of RepU derived from spent power reactor fuel imported from France. Over seven years, SGChE processed a total of about 1700 tonnes RepU. The SGChE has capacities to process up to 1500 tonnes of RepU per year with further rendering enrichment services totalling about 1 million SWU.

'AREVA's experience and future project for reprocessed uranium management' were the subjects of the third paper [MOREL, et al.]. AREVA has significant experience in managing RepU from reprocessing to the fabrication of ERU fuel assemblies. Particularly, AREVA has separated more than 22 000 tonnes of RepU from light water reactor (LWR) spent fuel at La Hague, plus about 4600 tonnes of RepU from spent gas-cooled reactor (GCR) fuel. AREVA sent the material to Pierrelatte in the form of uranyl nitrate hexahydrate (UNH) for conversion into U_3O_8 or UF_6, according to the recycling routes chosen by RepU owners. The two de-nitrification facilities in Pierrelatte convert UNH into U_3O_8 to be stored prior to its future recycling. The conversion facility of Comurhex has converted RepU from various customers since 1972. Two of those three facilities are scheduled to be shut down at the end of 2008, TU5 being the sole unit remaining in operation. The fabrication plant of FBFC at Romans has been manufacturing ERU fuel assemblies since 1993 (see also second paper of Session 3). Based on its large experience of managing RepU, taking into account the technical constraints and the evolution of the characteristics of the recovered material, AREVA has a project to invest in various new units offering the totality of services necessary for the recycling of RepU. This project comprises a new conversion facility, the capability to directly enrich RepU (in form of UF_6) in the Georges Besse II enrichment facility, several other support facilities covering necessary services for the recycling of RepU and logistics services. The new facilities will provide for minimized lead times of the ERU fuel manufacturing process. The realization of this project is dependent on the customers' commitments to recycle significant RepU quantities on a long-term basis. The facilities would be integrated on the Tricastin site.

The fourth paper [KOLUPAEV, et al.] dealt with 'Reprocessing of spent nuclear fuel at the PA Mayak and using reprocessed uranium'. The paper briefly stated the experience of Russian Federation's first and only spent nuclear fuel reprocessing plant RT-1 and the experience of RepU handling including foreign origin uranium (from COGEMA). Some current issues were reflected which are connected with increased NPP fuel burnups. Methods of uranium isotopic composition control were given in the paper. Furthermore, methods which can be used at PA 'Mayak' in future were considered.

The fifth and last paper [MURATA] in this session described 'Reprocessed uranium experience on conversion and enrichment in Japan'. As Japan is poor in uranium resources, RepU could become a valuable energy sources. The research and development of the conversion process for RepU has been

conducted at JAEA since the 1970s. Consecutive approaches to further develop the conversion of RepU were performed in the period 1982-1999, ending with practical application studies. This paper introduced the obtained achievements on which the construction of a future commercial RepU conversion facility will be based, particularly the establishment of the UO_3 hydration process and associated operating conditions.

Summary of the first Floor Discussion: 'RepU: Too hot to handle?'

Reprocessed uranium arising at the reprocessing plants becomes available in at least two different chemical forms (U_3O_8 and UO_3) and the industry has to cope with these forms, notwithstanding the fact that two different types of transport or storage canisters had to be developed. The industry should investigate whether standardization is achievable. If the industry has to invest in new facilities, having just one kind of product (meaning only one chemical form of RepU) and just one kind of package would ease all the logistics and the licensing. However, some utility representatives asserted that the service providers are still 'keeping a monopoly' on the material management. In view of that some TM participants argued that it would be much better to have one type of product in one unified commercial industrial system for the transportation and storage of RepU and ERU. If one is looking forward for standardization, first of all one has to look for cooperation, as mentioned in several of the papers presented at the TM and by several TM participants in the Floor Discussions. They stated that if there would be an evolution of a real RepU services market, this would most likely happen on an international basis and on a cooperative basis. Enhanced cooperation would most likely stimulate standardization.

There were several presentations on the potential future routes for the processing of RepU. Particularly, there were discussions about the conversion of RepU, its direct (physical) enrichments and about the blending route. The questions addressed during the floor discussion were: Which route would you favour? Which route would run the risk of minimizing the in-reactor performance of ERU fuel and which one would optimize ERU fuel performance? Many TM participants acknowledged the fact that the industry will have to go through the direct enrichment route, at least over the longer term. This is because of the limited availability of MEU and/or HEU as blending material. Accordingly, ways to get rid of unwanted even uranium isotopes in ERU have been discussed. In this context the Russian participants of the TM talked about the double cascading system (to decrease the ^{232}U and ^{236}U assays). The idea of a double cascade is not new. The concept of such system was developed some years ago and the economical efficiency of this double cascade has been assessed. Strategy issues have been discussed because RepU could potentially have a high value. In the UK, a fully flexible cost model has been developed. After the discussion with the UK government, one outcome was that the storage of RepU as waste (and its final disposal later on) is not a viable option. Instead, re-use is an option. However, there is no policy in the UK for the future construction and operation of fast reactors into which RepU could be loaded.

Because RepU is a consequence of reprocessing and because processing of RepU generates some more waste, one question discussed was: Could RepU be considered as a reprocessing waste? What about 'second generation waste' arising from the reprocessing of spent ERU fuel? Participants acknowledged that one has to be careful when talking about fissile material as a waste. Indeed, this categorization of RepU as fissile material, as waste or as a resource is depending on the economic value assumed for the said material.

5. Session 5: Utility experience and potential use

This session was particularly rich in information concerning the experience with the recycling of RepU (derived from spent LWR fuel) in form of ERU fuel produced via the blending route and loaded into a large-size BWR and large- and medium-size PWRs. Likewise, this session dealt also with ERU

fuel produced from physically enriched RepU loaded into PWRs of the 900 MWe size. The operation performance of all this fuel was excellent and differed very little – if any – from the performance of ordinary ENU fuel. The session dealt also with the radiological and technical problems in the recycling of higher burnup RepU (>33 GWd/t HM) in case of physical enrichment in centrifuges. Several papers clearly stated the utilities' view on what is needed in the nuclear infrastructure and in nuclear licensing in order to promote the large-scale recycling of RepU. One paper dealt with low burnup RepU regained from spent Indian PHWR fuel recycled directly (without blending or physical enrichment) into initial PHWR cores for neutron flux flattening purposes. Another paper dealt with analyses concerning the unique technical and cost-saving features of RepU obtained from the reprocessing of spent LWR fuel and recycled into CANDU-6 reactors.

The first paper [SCHRADER] in this session was entitled 'Reprocessed uranium: 5 years of operational experience in the Gundremmingen B BWR', an NPP operated by the German utility RWE Power AG. Starting in the year 2002, RWE has inserted in total 316 fuel assemblies with RepU into the core of this reactor up to now. These fuel assemblies were of the AREVA ATRIUM 10x10 type and have been manufactured by OAO Mashinostroitelny Zavod (OAO MSZ) at Elektrostal near Moscow (Russian Federation). The presentation of the operational experience of RepU within a mixed BWR core consisting of ENU, ERU and MOX fuel assemblies covered licensing issues, core management, core tracking (comparison of calculations and measurements), theoretical and practical influence of reactivity loss due to 236U, and mechanical behaviour. The overall operational experience with ERU fuel in the Gundremmingen B reactor is as good as the one with 'normal' ENU fuel assemblies.

The second paper [BAUMGAERTNER] in this session was on 'The use of reprocessed uranium in light water reactors: Problem identification and solution finding'. Of the three main options available to the German utility Energie Baden-Wuerttemberg (EnBW) for the use of RepU to produce ERU fuel assemblies two have been used: the enrichment by centrifuges and the blending with highly enriched uranium (HEU). The decision in favour of these two options was influenced by commercial and technical conditions. Importantly, the facts stated in this paper made clear that it is implicitly necessary to identify for each individual reactor as early as possible technical and legal limits and hurdles, to clarify which possibilities may be realized to assure the use of RepU in the first generation and the following ones. The ever increasing spent fuel burnups reduce the residual content of ^{235}U and increase the content of ^{236}U in RepU, i.e. lead to an inferior RepU quality. This, in turn, requires higher enrichment levels for both the blending and the centrifuge options. High ^{236}U content may even render the centrifuge option impossible. In addition, blending RepU with HEU to create ERU helps to solve the problems in connection with increased ^{232}U, ^{234}U and ^{236}U content and it helps to destroy (or at least diminish) HEU that could be hazardous. To safe costs, for utilities with options in reprocessing contracts an early decision is necessary about the form in which RepU will be returned. The expenses for conversion of UNH into U_3O_8 (for blending) or UF_6 (for enrichment via centrifuges) as well as for the subsequent storage of the converted product vary considerably. Since reprocessing means separation of uranium and plutonium, the recyclability of both products is required. A further important point is, therefore, to respect the limits of existing reprocessing and MOX fabrication plants. In the technical specification for projected facilities this should be considered - where feasible - to avoid problems in future. The adaptations of licensing values for NPPs as well as for facilities of the various processing steps in the nuclear fuel cycle have to be launched in good time to guarantee undisturbed treatment of future RepU quantities. The same is valid for licensing procedures for all means of transport, such as cylinders, containers and flasks for Unat, RepU and ERU as well as for transport and storage casks for fresh and irradiated fuel. According to the author, it is obvious that a well-timed forward planning is absolutely necessary and a prerequisite for a successful RepU recycling strategy.

The third paper [OLIVE, et al.] in this session was on 'Necessary conditions for the development of reprocessed uranium recycling'. Electricite de France (EDF) has gathered a strong experience in the recycling of physically enriched RepU since the first ERU fuel assembly was loaded in 1987. Describing the history and the lessons learned from experiments of RepU recycling and of regular ERU fuel loading the authors underlined that EDF did not register any negative impact of ERU fuel on the performance of its reactors. Nevertheless, EDF foresees difficulties and both technical and economic challenges which have to be solved and overcome in order to allow RepU play a more significant role in the nuclear fuel supply. However, this will be possible only if suppliers of nuclear fuel services are able to overcome present limitations and to offer additional capacities for the production of ERU fuel at competitive prices. Higher burnups of ENU fuel lead to an increased concentration of minor (even) isotopes in the recovered RepU and make it more difficult to recycle the material. In order to get round these obstacles, technical solutions must be found and investments may have to be made in the front end part of the ERU fuel cycle. Particularly, suppliers and utilities should also work together in order to increase the present limit of 5% ^{235}U enrichment in the international regulations and standards, at least for ERU fuel. Furthermore, the specifications of fabrication plants must be reassessed so that they can accept ERU with a higher 232U assay.

'Neutronic aspects of in-core fuel management with enriched reprocessed uranium – Belgian experience' was the title of the fourth presentation [DRUENNE, et al.]. ERU fuel has been loaded in the Belgian Doel-1 reactor up to 100% of the core with no specific licensing requirements. The lack of reactivity resulting from the ^{234}U and ^{236}U content needed to be compensated by an over-enrichment or, at constant enrichment, by additional fresh fuel assemblies. Comparison with similar In-Core Fuel Management (ICFM) (same cycle length, same enrichment) performed with ENU fuel showed that the impact of ERU fuel on the main neutronic parameters was small, or had the same order of magnitude as the change in In-Core Fuel Management had. The dose rate of fresh ERU fuel, although initially non significant, increases with time. Therefore, it has been recommended to store fresh ERU fuel assemblies in the pool and not in dry storage. Finally, the main restriction comes from the ^{232}U content, and time delay between conversion and transport becomes relevant.

The fifth paper [WIEMAN] described 'Thirty years of experience with reprocessed uranium management in Borssele'. This PWR (start-up in 1973) owned/operated by EPZ is the only operating NPP in The Netherlands. In 1976, the first contract for reprocessing its spent fuel in the La Hague reprocessing facility was signed, and subsequent reprocessing contracts cover fuel arisings until 2015. In the first twenty years of plant operations, EPZ's RepU has either been returned to the enrichment plant or has been sold off. More recently, EPZ has decided to recycle its RepU in its own reactor. This recycling has been implemented since 2003. As EPZ's fuel fabricator was not licensed to handle enriched uranium other than from natural feedstock, a co-operation with the company OAO MSZ at Elektrostal (Russian Federation) via a contract with AREVA NP was launched. OAO MSZ has enriched batches of EPZ's RepU and has produced the UO_2 pellets for two reloads of the Borssele reactor. EPZ's decision to recyle and not to dispose of RepU was based on economical arguments. However, this decision was in line with the company's policy to minimise waste for disposal and to recycle materials whenever possible. As a result of recent lawmaking in France, the intention to recycle RepU will have to be confirmed by the respective governments of The Netherlands and France in the form of an intergovernmental agreement. Such an agreement is presently under negotiation. EPZ has identified five options for managing future RepU arisings which according to preference are: the enrichment by blending and recycling of the fuel in the Borssele reactor; the physical enrichment in an enrichment plant and recycling of the fuel in the Borssele reactor; the transfer of title to third parties who intend to re-use the material themselves; the long-term storage of the uranium in France as oxide or fluoride; and the long-term storage as oxide in The Netherlands. Of course, the first two options for recycling in Borssele are only available as long as the plant is operating; they will disappear with the plant's scheduled shutdown in 2034. Thus, other options than recycling must be used as well.

The fifth paper [GROUILLER, et al.] in this session was entitled 'Reprocessed uranium recycled in PWRs: Impact on the core of reactor and on the fuel cycle'. The presence of ^{234}U and ^{236}U requires over-enrichment in ^{235}U for the recycling of the RepU in PWRs in the form of UO_2 fuel. For burnup rates of 55 GWd/t HM, the required ^{235}U assay of ERU fuel very quickly reaches 5% with traditional processes like ultra centrifugation. The emission of γ radiations by the decay products of ^{232}U requires significant biological protections for all the operations in the front end of the nuclear fuel cycle. The recycling of the RepU the production of plutonium in the ERU fuel by approximately 10% with a strong increase of ^{238}Pu which will have an impact on thermal power in the processes of the fuel reprocessing. The production of neptunium is also significantly increased up to a factor of 4. The production of curium is slightly decreased. The first recycling of the RepU in PWRs would allow to reduce the needs for natural uranium by approximately 10%. The authors conclude that the enrichment of RepU by the industrial centrifuge process is a benefit solution (profit in enrichment) for RepU issued from the standard UO_2 fuel having reached a burnup rate of about 33 GWd/t HM. However, for the burnup rates higher than those usually considered, or for multiple recycling, enrichment by non-selective technologies like centrifugation is not profitable (loss in enrichment). Reprocessing of corresponding irradiated fuel poses problems with the current processes, because of the very high 238Pu contents.

The seventh paper [ANANTHARAMAN, et al.] described the 'Utilization of reprocessed uranium in Indian reactors'. The fact that the closed fuel cycle option with the reprocessing and recycling of uranium and plutonium allows better utilisation of the uranium resources is getting particular significance in the context of India's nuclear power programme, due to the country's limited uranium and vast thorium resources. The recycling of uranium in thermal reactors has been driven by two factors: firstly, it does not call for significant changes in the thermal reactor fuel cycle facilities and secondly, it will not affect the recycling in fast reactors in the future. This paper highlighted India's perception about uranium recycling, its experience, and its future programmes. The authors stressed that uranium recycling in Indian PHWRs is different from that in most other countries (which employ LWRs with LEU as fuel) as the lower burnups in PHWRs provide an inherent advantage in terms of radiological consequences.

The eighth and last paper [HORHOIANU, et al.] in this session explained in detail the 'Technical feasibility of the use of RU-43 fuel in CANDU-6 reactors of the Cernavoda NPP'. A fissile content in the RepU regained from spent LWR fuel with a ^{235}U content of 0.9 to 1.0% makes it impossible for direct re-use in an LWR without prior enrichment. But CANDU reactors have a sufficiently high neutron economy to use RepU as fuel. The Romanian Institute for Nuclear Research (INR) Pitesti has analyzed the feasibility of using RepU fuel with 0.9-1.1w/o ^{235}U in the CANDU-6 reactors of the Cernavoda NPP. Using RepU fuel would produce a significant increase in the fuel discharge burnup, from 170 MWh/kg U currently achieved with natural uranium fuel to about 355 MWh/kg U. This would lead to reduced fuel cycle costs and a large reduction in the spent fuel volume per full power year of operation. The RepU fuel bundle design known as RU-43 is being developed by INR Pitesti and is now in the stage of final design verification. Early work has concentrated on RU-43 fuel bundle design optimization, safety and reactor physics assessment. The changes in fuel element (rod) and fuel bundle design contribute to the many advantages offered by the RU-43 bundle. Verification of the design of the RU-43 fuel bundle is performed in a way that shows that design criteria are met and it is mostly covered by proof tests, such as flow and irradiation tests. The most relevant calculations performed on this fuel bundle design version were presented in this paper. Also, the stages of an experimental program aiming to verify the operating performance were briefly described.

Summary of the second Floor Discussion: 'Can suppliers meet utilities' current and future needs?'

Today, for the utilities there are several ways and means to recycle RepU into reactors. Thus, outsiders could get the impression that the use of RepU does not pose major problems. Indeed, most of the utilities' needs concerning RepU management are met, but some of the solutions may be far away from representing the technical and commercial optimum. Those nuclear utilities which have not yet used up all their RepU inventories are still assessing and discussing what is missing in terms of modern, safe and economically efficient RepU processing facilities and what is missing in the licensing environment. Particularly, the utilities are pushing to have new facilities for the conversion of RepU into the form of UF_6. Again, standardization of the chemical form of RepU arising from the reprocessing plants is desired by the utilites, be it in the form of UO_3 or U_3O_8. However, suppliers of RepU processing services object that without the evolution of any market or substantial firm RepU processing commitments the from the utilities nobody on the industry's side would invest, not knowing whether additional investments in existing and/or new facilities would finally pay out. Notwithstanding, the suppliers have innovative ideas and they are the ones able to asses the actual costs of the different RepU enrichment routes (blending, mixed route, or physically enrichment).

The TM participants discussed the economic aspects of ERU fuel performance. There was a broad consensus that the industry needs solutions to minimize the over-enrichment of RepU in ^{235}U, especially knowing that every reactor operator has a very keen interest in optimizing its fuel management. Modern fuel management schemes involve ^{235}U enrichments between 4% and 5% for ENU fuel, meaning that physically enriched ERU would have to go above the 5% ^{235}U limit to achieve the same performance as ENU, exposing the industry to another category of problems.

The question was raised whether achieving equal performance of ERU and ENU fuel is really a must or if the utilities should move forward with loading ERU fuel which is under-performing. The utilities answered that they would accept the latter approach, provided there would be a large discount on the ERU fuel price. This answer is based on the fact that some utilities made individual studies about the lack of ERU fuel performance and economics and concluded that it would theoretically be possible to compensate this lack by lower fuel cost. However, related price reduction had to be very high in order to be acceptable. The reason for such high discount is simple: If an NPP cannot operate at its nominal capacity, this NPP's economics deteriorate, given the high fixed costs associated with nuclear energy generation.Some utilities which are not over-enriching their RepU are compensating the under-performance of their ERU fuel assemblies by larger reload batches (loading more assemblies per cycle). However, these utilities will have to put more spent fuel assemblies into casks, in order to dispose them of. This approach requires additional spent fuel storage capacities, thus raising the overall RepU management costs.The service suppliers argued that when discussing with their customers what they could do for them the outcome largely depends on what the customers are willing to pay for the required/offered services.

The challenge for the industry is to come up with ways or solutions, with innovative ideas to try to reduce the over-enrichment. This challenge can be met with a mix of technical innovations, but maybe also through an international cooperation between suppliers. The TM participants stated that the industry has to find a good mix of competition and cooperation.

6. Session 6: Economics, market aspects, and long-term perspectives of RepU utilization

There were four papers presented on this subject area. Under long-term energy supply security and environmental aspects, the most important objectives of the recycling of fissile and fertile materials are the efficient utilization of natural resources and the reduction of the overall waste. The latter is strongly dependent on the development of new nuclear energy systems as well as on the demand for

nuclear energy. Many utilities, however, take a different, more short-term oriented approach as from their point of view RepU recycling is driven mainly by economics and market aspects of the material. In order to assess the longer-term economic viability of the thermal recycling of RepU, the actual conversion (to UF_6), enrichment and fabrication route in Western facilities probably is the relevant model to assume. Today the blending of RepU with higher enriched uranium in Russian Federation is an established alternative but it may not be available over the longer term. So far generally it has been assumed that the RepU itself is gratis, i.e., a consequence of reprocessing that was performed for other reasons. RepU that is not recycled would have a negative value, since costs for a disposal route would be incurred.

The title of the first paper [TANAKA, et al.] 'The current status of reprocessing plants and MOX fuel fabrication facility in Japan' suggested that this paper had little to do with RepU. However, the contrary was the case, given Japan's particular proliferation-resistant approach towards the joint recycling of RepU and plutonium as MOX fuel. Japan has two reprocessing plants: The Tokai Reprocessing Plant (TRP) is in operation and the Rokkasho Reprocessing Plant (RRP) is in final tests before start-up. TRP is owned by the Japan Atomic Energy Agency (JAEA). It is in operation since 1977. By March 2007, this plant had reprocessed spent fuel totalling 1136 t HM. JAEA has been thinking about four methods to re-use RepU: its enrichment, its usage in form of mixed uranium-plutonium oxide (MOX) fuel, the mixing of this RepU with depleted uranium and its storage. This paper introduced the MOX fuel fabrication technology obtained by the Tokai Works. JNFL will have constructed a MOX fuel plant by 2012. Finally, the paper provided the current status of RRP and the near-term perspectives for RepU in Japan.

The second paper [VARLEY] entitled 'Reprocessed Uranium: Commercial resource or liability' discussed in detail the value of RepU which is a function of different cost/price parameters. The presence of minor uranium isotopes and their daughter products in RepU has logistics and cost implications for the recycling of the material. Whether or not RepU has a net asset value depends on the extent of any fuel service premiums that may apply, as well as the evolution of prices in the various sectors of the fresh uranium fuel cycle route. Natural uranium prices today make RepU recycling look attractive, but prices can and will change in the future. In addition, the economic view of recycling varies depending on whether or not the material is already recovered and stockpiled, or if it is a prospective product that could be recovered in existing or possible new reprocessing plants. This paper provided, in overview, a basis for assessing the conditions under which RepU may be considered a resource or a liability. Furthermore, it provided perspectives on the future evolution of front end commodity and service prices and the implications for the economic interest in recycling. From the author's point of view, in order to stimulate RepU recycling the key investment area is conversion, to facilitate greater utilization of the Western centrifuge enrichment capacity capable of enriching RepU. However, any supplier considering new investment in conversion capacity must be prudent as the economic incentives to recycle could become marginal once the uranium market settles after current high prices.

The third paper [TEYSSIER, et al.] dealt with the question: 'Can reprocessed uranium become the most natural substitute to uranium?' The current rally in uranium prices has arisen many concerns about uranium supply. If the recent uranium price evolution had really sent a strong signal to the nuclear community, the gap between natural uranium production and world demand would not last long. However, it seems that front end market actors are still not primarily thinking about RepU to fill in the primary supply-demand gap. This paper presented the current market fundamentals and front end market trends, examined the solutions envisaged to respond to utility needs, and analyzed the current positioning of RepU and the reasons of its current small market share. It analyzed the value elements of a RepU offering, according to a standardized marketing methodology, and tried to define avenues worth exploring.

The fourth and last paper [BAIRIOT] of this session was on the 'Impact on market conditions on the economics of RepU recycling'. The paper analysed in detail the cost of ERU fuel, as a function of RepU quality, market prices of the fuel cycle front end, enrichment technology and design discharge burnup of the ERU fuel. The results are one input to a decision on whether to utilize available RepU in the short term to benefit from attractive enrichment conditions or to store it as strategic reserve to be used later. Besides economic evaluations, other factors were also to be taken into consideration, such as perspectives of future burnup increases, evolution of the regulatory limitations and political decision to phase-out nuclear energy. The data presented in the paper have no absolute value, since this paper did not aim at being exhaustive, but only to show sensitivity to market prices. It took one case: ERU fuel which is equivalent to 4.4% enriched ENU, to be manufactured from RepU issued from spent fuel discharged at three different burnups. The three RepU enrichment processes used up to now were considered: centrifuge, blending with unirradiated enriched uranium and blending with medium enriched uranium (MEU) gained from reprocessing. No attempt was made to optimize the economics by adjusting the tails assay, the ^{235}U assay of the enriched uranium blendstock, etc. ERU from blending with unirradiated enriched uranium was competitive in the past, but is not competitive any longer and will continue to be even more expensive in the future. With the two other RepU enrichment options (centrifuge enrichment and blending with MEU), ERU is currently less expensive than ENU and this competitiveness will increase in the future. But centrifuge enrichment can not be applied to RepU issued from higher burnup spent fuel, since the current 5% ^{235}U limit would be exceeded.

Summary of the third Floor Discussion on 'Management of RepU: What do we have? What do we need? What is missing?'

The TM participants stressed that it is quite easy to optimize the total costs of an ENU assembly because there is a market price for U_3O_8, conversion, enrichment, fuel assembly manufacturing and transport services. As regards ERU fuel, cost optimization is not so easy, as quite a lot of different aspects have to be considered and as there is no highly diversified and developed market for RepU processing services. Some TM participants argued, however, that Russian Federation represents a good example for its internal optimization of the ERU fuel supply chain.

In the case of RepU, the utilities generally put a zero value to it. To turn it into a valuable reserve, e.g. into ERU in form of UF_6, agreements have to be found between the utility and the service suppliers, including some form of contractual guaranty for the suppliers concerning the processing of substantial RepU volumes which give them a reasonable return on investment over the lifetime of their facilities.

Individual TM participants stated that reprocessing should go hand in hand with long-term thoughts about fast breeder reactors because reprocessing just for the thermal recycling of RepU does not make very much sense. Indeed, historically the initial long-term objective of reprocessing was going to fast neutron reactors.

The issue of direct use of RepU in PHWRs was discussed. The key issue with PHWRs is the amount of spent fuel to handle. Another issue is the transfer of RepU from one utility to another one because, except for Korea and India, there are no countries which are operating LWRs and PHWRs simultaneously. International and national legal frameworks would be required to ease the transfer of RepU. Russian Federation objected that gaining experience in this area started already around 10 years ago. At that time, Russian Federation successfully received RepU material from France and the UK and successfully sent back the components of nuclear fuel assemblies (pellets) to Germany, for eventual use in German reactors and in NPP units of several other countries. All transports were done according to the national and international legislation and laws.

In the longer-term, installed nuclear generating capacities are currently expected to grow considerably, leading to a larger spent fuel accumulation. Thus, one has to consider issues such as repositories, social costs, etc., which are more complex issues than just the uranium market economic estimation.

7. Conclusions

Potentials of, and challenges in RepU recycling well understood

The participants of the Technical Meeting represented all pertinent areas of the employment of RepU, namely fuel cycle analysis, fuel fabricators, utilities, regulators, reprocessors and service providers. Furthermore, some preliminary points of view of few Governmental Organizations were forwarded. The TM attempted to give a comprehensive picture of technical as well as economical aspects of the management of RepU. An important outcome of the TM was the global understanding of the immense potentials, opportunities and challenges in the utilization of RepU.

Part of Western RepU recycling infrastructure disappeared

Concerning RepU there is far less compelling international pressure to avoid unnecessary accumulation of the material than there is for plutonium. Nevertheless, given the previous perception of a potential future uranium shortage, starting roughly two decades ago the industry put in place the facilities which were needed to take benefit of RepU. This included chemical conversion, storage of RepU in oxide form, purification prior to enrichment, enrichment itself, fuel fabrication and transport as well as reactor irradiation. Different recycling methodologies have been developed, tested, and successfully pursued - some even on semi-industrial scale - in Europe, India, Japan, Russian Federation and elsewhere. Appropriate actions have been carried out in order to minimize RepU's radiological impacts and to properly and safely run the concerned facilities and plants. Nevertheless, cheap natural uranium and secondary sources such as Russian Federationn downblended weapons-grade uranium choke off most of the demand for RepU and, therefore, part of the Western infrastructure for RepU recycling disappeared.

Russian infrastructure assures ongoing RepU recycling

However, due to the Russian infrastructure (purification, conversion and enrichment of RepU at the Siberian Group of Chemical Enterprises (SGChE) and re-conversion and ERU fuel fabrication at Elektrostal) and the Russian availability of MEU as blending material the recycling of Western and Russian RepU is going on. Accordingly, significant additional experience is continuously accumulated by the industry, particularly in the logistics associated with RepU and in ERU fuel performance. However, Russian MEU resources appear to be finite, and the production of fresh MEU for blending purposes appears to be uneconomic. Furthermore, the facilities of SGChE could be augmented to handle a greater annual throughput of Western RepU, but this may not be acceptable or possible for political/institutional or commercial/competitive reasons.

Practicability of enrichment of RepU and excellent performance of ERU fuel in LWRs

Experience has proven the practicability of both RepU enrichment alternatives, i.e. centrifuge enrichment and blending (see above), without major difficulties. The overall operational experience with ERU fuel in light water reactors is as good as the one with ENU fuel. The utilities have learned that adaptations of licensing values for NPPs as well as for facilities of the various processing steps in the nuclear fuel cycle have to be launched in good time to guarantee undisturbed treatment of future RepU quantities. The same is valid for licensing procedures for all means of transport, such as cylinders, containers and flasks for Unat, RepU, ERU as well as transport and storage casks for fresh and irradiated fuel. It is obvious that a well-timed forward planning is absolutely necessary and a prerequisite for a successful RepU recycling strategy.

Additional options for the usage of RepU have been demonstrated, such as the direct recycling of RepU from Indian PHWRs into initial cores of PHWRs. Furthermore, the direct recycling of RepU into CANDU reactors is expected to yield unique technical and cost-saving features.

Plans for future RepU management projects on stand-by

For many different reasons, among them also national policies or perceived public opposition, currently no country - except France and Japan - forecasts the use of RepU beyond 2015. In order to get round the technical and commercial obstacles preventing the revival of the reprocessing option and a larger-scale recycling of RepU, technical solutions must be found and investments have to be made in the front end part of the ERU fuel cycle. Particularly, new conversion and additional enrichment capacities are needed. The centrifuge technology, because it is modular, allows to devote specific cascades to RepU enrichment, which is not possible with gaseous diffusion. Suppliers and utilities should work together in order to increase the present limit of 5% ^{235}U enrichment in the international regulations and standards, at least for ERU fuel. The specifications of fabrication plants must be reassessed so that they can accept ERU with a higher ^{232}U assay. Sophisticated plans have already been drafted for the construction of future RepU management projects. However, most of these plans will become reality only in case customers would commit themselves to recycle significant RepU quantities on a long-term basis.

Economics of future RepU recycling - A lot depends on natural uranium market price levels

Where national policies and perceived public opposition do NOT inhibit reprocessing and recycling of plutonium and RepU, actual recycling of reprocessed uranium is to a large extent dependent on the economics. In order to assess the longer-term economic viability of RepU recycling, the actual conversion (to UF_6), the physical enrichment and the fabrication route in Western facilities probably is the relevant model to assume. Taking the actual enrichment route as an example, therefore, an estimate of the economic break-even point between fresh uranium fuel and RepU fuel may be calculated. It is dependent on the isotopic composition of the RepU (principally the ^{235}U content) and to a large extent on the cost for conversion. Enrichment and fabrication premiums play a secondary role. So far generally it has been assumed that the RepU itself is gratis, i.e., a consequence of reprocessing that was performed for other reasons. Strictly speaking the economic value of recycling RepU should be assessed as one element of the overall cost associated with spent fuel management involving reprocessing and this certainly would be the case for any new entrant to reprocessing.

8. Suggestions for future work

In addition to the three isotopes ^{234}U, ^{235}U and ^{238}U contained in natural uranium, RepU contains four additional isotopes: ^{232}U, ^{233}U, ^{236}U and ^{237}U. The ^{234}U and ^{236}U isotopes are neutron absorbing isotopes and over-enrichment of ^{235}U is needed to compensate the lack of reactivity compared to equivalent ENU fuel assemblies. At constant enrichment in ^{235}U, additional assemblies would be needed to keep the same energy production. The ‘neutron-absorber credit’ is especially relevant to the licensing procedures for RepU transportation and storage. The Safety Authorities do not generally differentiate for criticality calculations between ERU and ENU fuel assemblies. Thus, the presence of neutron absorbers in the ERU fuel is not taken into account. It is suggested to consider suitable evaluations and the possible incorporation of a neutron absorber credit for ERU-based fuel which would enhance the recycling options of RepU.

The fissile content in the RepU from spent LWR fuel could be in the range of 0.9 to 1.0% and thus makes it possible for direct reuse (without enrichment of RepU) in CANDUs and PHWRs with a sufficiently high neutron economy. This would lead to reduced fuel cycle cost and a large reduction in the spent fuel volume per full-power-year of operation. Several Member States (viz., Russian

Federation, Romania, Korea, and India) expressed interest in initiating a detailed study on the potential usability of RepU in PHWRs.

In the longer term, the RepU tails has exactly the same potential for use in fast reactors as depleted uranium (DepU) from the enrichment of natural uranium. Hence, it is suggested that the IAEA initiates a project on 'recycling aspects of RepU and DepU in fast reactors'.

The TM also recognized the need to transition to >5% ^{235}U in utilisation of ERU in commercial power reactor fuels. The enrichments in excess of 5% ^{235}U will result in ERU fuel with different isotopic characteristics (especially higher concentrations of the minor isotopes ^{232}U, ^{234}U and ^{236}U) which change the economics balance for the recycling of RepU. This move to higher than 5% would be a significant operational step for both the ERU- and the ENU-based fuel industry. There would be significant regulatory and safety issues to be addressed and to be overcome, including revisions to current operating licenses.

MANAGEMENT OF RepU: RECENT IAEA AND OECD ANALYSES

(Session 1)

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Management of RepU: Recent analyses of the IAEA and new approach towards technical issues

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Abstract. Recognising the potential importance of reprocessed uranium (RepU) in hedging the 'Nuclear Renaissance' against nuclear fuel shortages, the IAEA has prepared a report aiming to review and summarize the information on the management of RepU (IAEA-TECDOC-1529 of February 2007 [1]). However, during the preparation of this TECDOC the impression intensified that there is a necessity to elaborate more on technical aspects of the processes involved in the utilization of RepU. In particular, at the IAEA the idea was born to produce another document, structured like a handbook for those who wish to use RepU for nuclear energy generation and who wish to provide services and products related to RepU.

1. Introduction

The idea of recycling or RepU is very simple, at least on paper: Take spent fuel elements discharged from a reactor, reprocess them, separate the remaining uranium and recycle it into the same or another reactor.

Since the start of the British Magnox program in the 1960s until mid-2004, more than 35 000 tonnes of RepU have been recovered by the reprocessing of slightly irradiated fuels. Thereof, more than 16 000 tonnes have been reconverted, re-enriched, fabricated into fuel for Advanced Gas-cooled Reactors (AGR) and loaded into British AGRs.

Likewise, the recycling of RepU that was obtained by the reprocessing of highly irradiated spent Light Water Reactor (LWR) fuels was ascertained and it performed acceptably. In 1983, a small batch of fuel using RepU (that was derived from the reprocessing of irradiated LWR fuels) was introduced in a German nuclear reactor. Since this starting point, the reprocessing plants have delivered more than 12 000 tonnes of RepU derived from spent LWR fuel. The industry quietly put in place the facilities which were needed to take benefit of RepU. This includes chemical conversion of RepU, storage of RepU in oxide form, purification prior to enrichment, enrichment itself, fuel fabrication and transport as well as reactor irradiation. Different recycling methodologies for RepU have been developed, tested, and successfully pursued - some even in semi-industrial scale - in Europe, India, Japan, Russia and elsewhere. Appropriate actions have been carried out in order to minimize RepU's radiological impacts and to properly and safely run the concerned facilities and plants. And significant additional operating experience is continuously accumulated by the industry in each step of the RepU on the operation and maintenance conditions.

RepU recycling is not only technically feasible, but it can have environmental benefits: It can reduce the volumes of spent fuel to be disposed of, and it can reduce the need for fresh uranium to be mined and milled. What is more, recycling of nuclear material could be important for the nuclear fuel cycle in the context of sustainable growth of nuclear energy. In fact: Security of energy supplies in general and nuclear energy in particular remain key issues on the world's political agenda. While the reprocessing and the use of enriched reprocessed uranium (ERU) and mixed oxide fuel (MOX) face difficulties because of the political decisions in some countries to postpone or abandon this solution for spent fuel management, rethinking has started in some other parts of the world. For example: In the

United States where reprocessing on an industrial scale has not been pursued before, serious consideration is now being given to this possibility.

2. In retrospect: Cheap natural uranium choke off demand for RepU

Despite all technical achievements mentioned above, today recycling of RepU is still limited to a fraction of the available material. While the worldwide installed nuclear electricity generation capacity of currently about 367 GWe which leaves behind spent nuclear fuel of about 10 000 tonnes of heavy metal (HM) annually, only a small portion of this quantity is reprocessed. Above all, just a fraction of the arising RepU is regularly recycled into Western-design LWRs and Russian-design light water-cooled, graphite-moderated reactors (RBMK).

Declarations made in the World Nuclear Association (WNA) [2] reflect the following overall situation:

- Only France declares a stable long-term policy for using RepU fuel.
- Some countries like Germany and Switzerland are using RepU only until their stockpile is completely used up.
- Japan is anticipating the usage of RepU fuel on a planned basis, in future.
- Some countries like the USA do not (yet) declare any foreseen use of RepU.

Moreover, except in France and Japan, no country forecasts the use of RepU beyond 2015.

It should be noted that in the case of RepU there is far less compelling international pressure to avoid unnecessary accumulation of the material than there is for plutonium. Nevertheless, the facts just mentioned suggest some urgent questions:

- Are there - despite above mentioned advances and encouraging technical experiences - any problems associated with the handling of the RepU, the operation of the existing RepU recycling infrastructure and/or the engineering and licensing of new facilities and new core designs with fuel made of RepU? Asked in brief: Is RepU too hot to handle?
- And what about the economics of RepU recycling: Does it actually pay off?
- Can suppliers - meaning the fuel cycle industries - meet the utilities' needs, or can't they yet?
- In the management of RepU: What do we have, what do we need, and what is missing?

The bulk of today's operating capacities for the reprocessing of LWR fuel were developed when natural uranium (Unat) prices were still high and - given anticipated huge nuclear power plant (NPP) capacity growth rates - expected to stay that way. However, an era of low uranium prices - from about 1980 to the turn of the last century - together with proliferation concerns of individual countries, drastically reduced most recycling plans, at least in the West. It became much cheaper and less cumbersome to go with a ‘once-through cycle’, even if that meant to leave significant amounts of untapped energy in the spent fuel. A partial compensation came from the trend towards higher burnup fuel designs, which not coincidentally diminishes the rewards of the recycling of future RepU.

While reprocessing programs that had entailed large capital investments continued, mainly in France, the United Kingdom (UK) and Russia, most of the resulting fuel was MOX, which takes advantage of plutonium recycling to save on enrichment. Yet RepU was destined to see its first chance pass into history. As long as fresh uranium was cheap, the special handling steps that RepU requires meant that it was generally uncompetitive with the fresh product.

3. Fundamentals of the natural uranium market changing in favor of RepU ?

In the last few years, natural uranium prices have seen a remarkable upswing, for a number of reasons:

- With the exception of downblended Russian weapons-grade highly enriched uranium (HEU) implicitly declared 'excess', secondary supplies, such as governmental and utility excess stockpiles, have largely dried out.
- Scheduled uranium production (defined as announced projects in which the supply is reasonably expected to become available) is not keeping up with increasing demand.
- There were different production downtimes of individual uranium producers (Olympic Dam and Ranger (Australia); McArthur River (Canada)).
- Due to technical problems, several new mines experienced delayed start-ups (Honeymoon (Australia); Vasquez (USA); Cigar Lake (Canada)).
- The market saw short-term purchases of producers who cannot meet upward delivery flexibilities granted under their long-term contracts.
- And Hedge Fonds' purchases in a tight market supported the upward price trend.

Natural uranium spot market prices increased by about a factor of sixteen between June 2001 and June 2007, jumping from US$ 8.65/lb U_3O_8 six years ago to US$ 136.00/lb U_3O_8 in June 2007 [3]. Likewise, starting prices charged under new long-term contracts went up by a factor of nine, from US$ 10.50/lb U_3O_8 then to US$ 95.00/lb U_3O_8 in June 2007.

4. Short and medium-term perspective for RepU

4.1. Are fuel managers giving RepU a 'second chance'?

Until new uranium production can catch up with demand, natural uranium prices can be expected to remain strong. Therefore, the following questions arise: Is RepU recycling economically attractive now? Are the utilities' fuel managers about to give RepU a 'second chance'? And is the infrastructure in place to do so?

In June 2007, at the 'Conference on 'Global Nuclear Fuel Reprocessing and Recycling' (GNR2)' [4] http://www.gnr2.org/pdf/program.pdfin Seattle (USA), several experts stressed that average realized uranium prices are still much below the current spot market prices and current starting prices charged under new long-term contracts:

- First, in 2006, Cameco, the world's leading uranium producer, achieved an average income of about US$ 21/lb U_3O_8.
- Second, the US Energy Information Administration (EIA) reported that in 2006 average prices paid by US utilities were just about US$ 18/lb U_3O_8 [5].
- Third, the European Supply Agency (ESA) disclosed in mid-June 2007 http://ec.europa.eu/euratom/ar/last.pdfthat the average prices paid in 2006 by EU utilities under their long-term contracts were US$ 18.55/lb U_3O_8 [6], just US$ 2.50/lb U_3O_8 up from the average price paid in 2005.

Refraining from an accurate, detailed economic assessment of RepU recycling, the quoted average prices suggest that large utilization of RepU may be still some years ahead. Indeed, individual utilities do not see the current economics of RepU recycling enticing enough to launch a new or extended RepU recycling program. General interest in RepU recycling does not yet counter the current obsession with securing long-term fresh uranium supplies in a market that seems to grow tighter almost every week.

Nevertheless, with the gradual expiration of the utilities' older legacy contracts stipulating low prices and with their replacement by higher-priced contracts concluded in the recent two or three year, the economics of RepU recycling are expected to increase substantially. Maybe the utilities' fuel managers will take RepU more seriously once they have secured most of their medium- and long-term uranium

needs and once they see the economic implications of their new, higher-priced uranium contracts more clearly.

4.2. Challenges in RepU recycling

As a matter of fact, RepU recycling entails some costly and tedious details: Much more paper work, intensified discussions with the regulators, new and/or additional spent fuel storage issues, and the like. Investment costs in engineering and licensing of new reactor core designs using enriched RepU (ERU) fuel may be substantial, and these may remain among the largest obstacles to any large increase in RepU recycling.

From a mere technical standpoint, the presence of ^{232}U in RepU and of its troublesome daughter Thallium-208 (^{208}Tl), a particularly hard gamma emitter, is probably the largest complicating factor inhibiting RepU's ready acceptance. Transporters, converters, enrichers and fuel fabricators must all be concerned of radiation risks, and the fuel itself might - depending on the history of the RepU contained in it - require special handling before being loaded into reactors. At a minimum, careful scheduling to assure speedy handling from purification to fuel loading is essential in order to minimize the time in which harmful isotopes can accumulate.

4.3. Is there room for RepU in the near-term uranium supply and demand balance?

When looking at the uranium demand and supply situation of Western-design reactors up to the year 2025 (Fig. 1), operating, currently planned and prospective uranium production, together with different secondary supplies, are expected to meet demand at least until about 2020. Accordingly, Figure 1 suggests that there is no niche in the market for additional RepU to enter it.

However, it cannot be taken for granted that all planned and prospective production will commence operation as currently planned. The existing and potential producers are facing many technical challenges, many social and political constraints, licensing and legal constraints, and so on. Thus, from the mere nuclear fuel demand and supply point of view RepU should find its way into the market.

4.4. Bottlenecks in the infrastructure of RepU recycling

Nevertheless, with respect to prospective market impacts, while current and future stocks of RepU are hardly insignificant (see below), material and/or capacity constraints could seriously inhibit a major market role for RepU in the years ahead:

Blending RepU with low-enriched uranium (LEU) (with up to 17% ^{235}U) is currently the most attractive recycling route, and this will apply as long as such material is available at low cost. Thus, blending of RepU with freshly produced LEU having such high ^{235}U assays is economically unattractive if current market prices have to be paid for the individual components of the material (vis., uranium, conversion and enrichment). The emerging shortage of cheap LEU (with up to 17% ^{235}U) may become - earlier or later - a large obstacle to broad-scale adoption of ERU fuel.

Besides blending, direct enrichment of RepU may also be an attractive recycling route. But such enrichment efforts entail dedicated enrichment lines to cope with contamination issues. While Russia is believed to have idle gas centrifuge capacities, Western enrichers' existing and planned capacities are obviously fully booked out throughout the foreseeable future. Thus, enrichment capacity constraints could prove to be another large constraint to industrial-scale recycling of RepU.

In short, while fuel prices alone are about to facilitate a ‘second chance’ for RepU, the ERU volumes entering the market in the years ahead are likely to be more a steady trickle than a market-changing flood. For the near and medium term, RepU cannot act as an alternative to new long-term uranium contracts. Rather, it may play just a supplementary role.

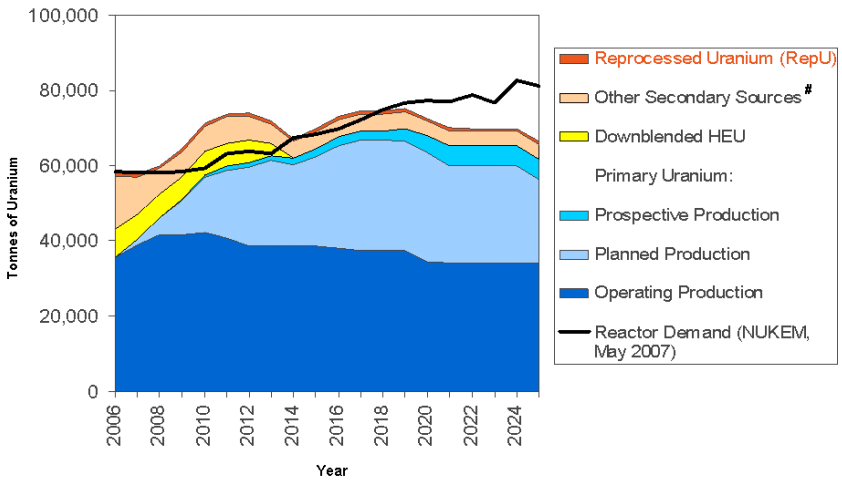

FIG. 1. Western world uranium demand and supply (reference case). # Other secondary sources include weapons plutonium, civil Pu, re-enriched tails and inventories. Source: NUKEM GmbH, internal data, Alzenau, Germany June 2007.

5. Longer-term perspective for RepU

Let me now move from 'What is here and now and will be in the short term' to 'What may be in the future'?

According to the 'Red Book' of the OECD/NEA & IAEA [7], the world's Reasonably Assured (RAR) plus Inferred Uranium Resources (IR) recoverable at costs up to US$ 130/kg are totalling 4.7 million tonnes U (see Table 1). Thus, uranium resources are not the limiting factor for increasing uranium production over the short and medium term.

TABLE 1. HOW MUCH URANIUM IS ENOUGH URANIUM? [7]

Reasonably Assured (RAR) plus Inferred Resources (IR) in 2007 (< US$ 130/kg U)	4 743 000 t U
Reactor Demand, 2007 – 2030 (not accounting for Secondary Supplies)	2 017 000 t U
Remaining Reasonably Assured plus Inferred Resources in 2030 (<US$ 130/kg U)	2 726 000 t U
Reactor Demand in 2030	~ 100 000 t U

Sources: Reference [7]; NUKEM GmbH, Internal data, Alzenau (Germany), July 2006.

However, the number of 4.7 million tonnes U (RAR and IR in total) compares to an aggregate demand of currently existing, planned and anticipated NPPs in the period 2007 to 2030 of 2.0 million tonnes U. This implies that in 2030 the remaining Reasonably Assured and Inferred Resources will not be sufficient to meet over longer periods the needs of the then installed NPP capacity of around 540 GWe. Only if Prognosticated plus Speculative Resources recoverable at costs up to US$ 130/kg would be taken into account, the uranium demand of an installed NPP capacity of 500 GWe plus could be met 100 years and more (see Table 2).

In brief: The world is not so rich in cheap uranium resources that it would be justified to forget about the fuel supply potentials of recyclable material, and of RepU in particular.

TABLE 2. NATURAL URANIUM RESOURCES BY CATEGORY

Resource Category	Quantity (in 1000 tU)	Coverage of Demand (in Years)	
		2007	2008
		368 GWe	534 GWe
		66 000 tU	100 000 Tu
Reasonably Assured plus Inferred Resources (< US$ 130/kg U)	4743	72	47
Prognosticated plus Speculative Resources (< US$ 130/kg U)	7077	107	70
Subtotal 1	**11 820**	**179**	**118**
Speculative Resources (no Cost Range assigned)	2980	45	30
Subtotal 2	**14 800**	**224**	**148**
Unconventional Uranium Resources			
- Phosphates	22 000	333	220
- Ocean Water (1% of Total)	40 000	600	400
Total	**76 800**	**1163**	**768**

Source: OECD/NEA; 'Uranium 2005: Resources, Production and Demand', 2006 [7].

Recently, the OECD prepared a report on 'Management of Recyclable Fissile and Fertile Materials' [8]. The next presentation within this Technical Meeting will give major findings and recommendations of this report. Nevertheless, let me draw your attention to some important facts on the inventory and energy content of recyclable materials given in this report. These materials do not comprise the military HEU and plutonium of the 'super powers' which have not (yet) been declared 'excess'. At year-end 2005, the natural uranium equivalent of these readily recyclable materials amounted to 645 000 tonnes U. This quantity translates into about 10 years of current worldwide uranium consumption, or the demand of 3840 reactor years (see Table 3). Thereof, RepU accounted for a natural uranium equivalent of 50 000 tonnes U, or the demand of 300 reactor years.

TABLE 3. INVENTORY OF SEPARATED RECYCLE FISSILE MATERIALS AT YEAR-END 2005

Supply Source	Quantity (tHM)	Unat Equivalent (tU)	Potential Supply in Reactor Years [1)]
Ex-military HEU	230 [2)]	70 000	420
Ex-military Pu	70	15 000	90
Pu	320	60 000	380
RepU	**45 000**	**50 000**	**300**
Enrichment Tails	1 600 000	450 000	2650
Total		**645 000**	**3840**

1) Based on a 1000 MWe LWR, operating at an 80% load factor; 2) Remaining inventories, taking into account the quantities already down-blended and re-used. Source: OECD/NEA; April 2007 [8].

Furthermore, at year-end 2005, there were roughly 200 000 tonnes spent fuel in storage, the vast majority of which was LWR fuel. Not all of this material may be suitable for reprocessing. Assuming, nevertheless, it would be reprocessed, the regained RepU would represent a natural uranium equivalent of about 190 000 tonnes U. And the annual spent fuel arisings of 10 000 tonnes represent – depending on the fuel's burnup – a natural uranium equivalent of about 8000–9000 t U. These quantities are truly more than a drop in a bucket.

6. Objectives and scope of the technical meeting on RepU

Recognising the potential importance of RepU in hedging the 'Nuclear Renaissance' against nuclear fuel shortages, the IAEA has recently prepared a report aiming to review and summarize the information on the management of reprocessed uranium (RepU) (IAEA-TECDOC-1529 of February 2007 [1]).

Here are both the merits and the weak points of this TecDoc:

- The document deals extensively with the characteristics of the uranium isotopes (and their decay products) which make up the RepU.

- It decribes the historic and current reprocessing activities by country which give rise to the production of RepU. In this context, data are given on historically regained RepU quantities.

- Likewise, the TECDOC describes the RepU management facilities by country, and it gives best estimates on RepU quantities which have already been recycled and which are still awaiting recycling. However, the information on both processing facilities and quantities is already partly outdated and needs to be updated and amended.

- The TECDOC describes in brief the different recycling possibilities, like direct recycling (such as for flux flattening in Heavy Water Reactors (HWR)), physical re-enrichment, blending with LEU (with ^{235}U assays up to 17%), using RepU as matrix for MOX fuel, and so on. But we wonder whether the information given in this TecDoc could be enriched further with many more technical aspects and details.

- The TecDoc reports on the utilities' experience with enriched RepU fuel in LWRs. Also on this subject additional and more in-depth information would be welcome.

- Immobilization and disposal of RepU were touched only briefly, as was also the management of spent RepU fuel. But these issues are not the focus of this Technical Meeting which will deal with re-use options.

- Market and economic issues were given only little attention in the TECDOC.

However, during the preparation of this Technical Meeting the impression intensified that there is a necessity to elaborate more on technical aspects of the processes involved in utilization of RepU. In particular, the idea was born to produce another document, structured like a handbook for those who wish to use RepU for nuclear energy generation and who wish to provide services and products related to RepU.

7. Technical aspects of RepU recycling of interest

The main idea of the new document is to present the existing options and their detailed analyses as well as approaches and future developments in the management of RepU. The document is planned to encompass the technical issues, such as RepU storage, chemical conversion, re-enrichment, fuel fabrication, transport, in-core fuel management, subsequent reprocessing and disposal options, as well as economic issues and long-term perspectives.

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Management of reprocessed uranium: Main findings from an NEA study

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Abstract. The paper, based on a report published by the OECD in 2007 on the management of recyclable fissile and fertile materials [1], covers various aspects of the storage, processing, re-use and/or eventual disposal of reprocessed uranium. The information provided by contributors to the study gives an overview of the amount of reprocessed uranium accumulated so far in stockpiles. Future arisings of reprocessed uranium are evaluated taking into account the expected evolutions of nuclear electricity generation and reprocessing capabilities. The alternative options available for the management of reprocessed uranium are described briefly and their respective advantages and drawbacks are reviewed. Concluding remarks focus on the challenges and opportunities offered by various options for the management of reprocessed uranium in a sustainable development perspective.

1. Introduction

Reprocessed uranium (RepU) is one of the materials considered in a recent Nuclear Energy Agency (NE) study on the management of recyclable materials, which was published in 2007. The study covers a broad range of materials including depleted uranium, plutonium from reprocessing and ex-military materials declared excess to national security by Russia and the United States, as well as reprocessed uranium.

The main objectives of the study were:

- to evaluate the inventories of recyclable materials existing worldwide;
- to identify and describe alternative options for the management of those materials including their technology preparedness and industrial maturity if applicable; and
- to review opportunities and challenges offered by various options.

The assessments carried out in the study aim at providing policy makers with relevant information and analyses for choices to be made regarding the management of recyclable materials, including reprocessed uranium, in a sustainable development perspective.

2. Inventories of depleted uranium

In the light of the choice made by many countries and operators in favour of the once-through fuel cycle, only a limited amount of spent fuel from commercial nuclear power plants (NPP) has been reprocessed. However, worldwide, the reprocessing of irradiated oxide fuel mainly from Light Water Reactors (LWR) but also from Advanced Gas-cooled Reactors (AGR) in the United Kingdom has produced significant quantities of reprocessed uranium.

The total inventory of RepU accumulated in stockpiles at the end of 2005 has been estimated at some 45 000 tonnes. Under past and present technical and economic conditions, immediate recycling of reprocessed uranium was not considered attractive in most cases. Therefore, most RepU has been converted from the liquid uranyl nitrate hexahydrate (UHN) form obtained after reprocessing into

forms better adapted to long-term storage – generally solid oxide forms, either UO_3 or U_3O_8 – and sent to storage facilities.

The energy content of RepU, expressed in weight of natural uranium equivalent, depends on the characteristics, e.g., reactor type and burnup, of the spent fuel reprocessed to obtain it. Based on average assumptions applicable to the fleet of reactors in operation in the world during previous decades, the inventory of RepU (45 000 tonnes) may be estimated to be equivalent to 50 000 tonnes of natural uranium, i.e., nearly one year of total annual consumption of natural uranium at the early 21st century rate.

Table 1 illustrates the relative importance of RepU as compared with other separated recyclable fissile materials in terms of potential energy content, expressed in years of fuel supply for 1000 MWe LWRs of current generation operating at 80% load factor. It shows that inventories of RepU could save significant amounts of fresh uranium but that they are by far not the most important recyclable fissile materials in terms of retrievable energy content.

TABLE 1. INVENTORY OF SEPARATED RECYCLABLE FISSILE MATERIALS AT THE END OF 2005

Material	Quantity (t HM)	Natural U Equivalent (t U)	Reactor Years of Supply
Ex-military HEU	230	70 000	420
Ex-military Pu	70	15 000	90
Pu	370	60 000	380
RepU	**45 000**	**50 000**	**300**
Enrichment tails	1 600 000	450 000	2650

The inventories of spent fuel amount to some 200 000 tonnes of heavy metal worldwide. Their reprocessing would provide a quantity of uranium representing about 190 000 tonnes of natural uranium equivalent, if and when the closed cycle route would be adopted. Looking ahead, spent fuel is arising from NPPs in operation at a rate of some 10 000 tonnes per year and if it were reprocessed it would provide a similar amount of uranium equivalent useable to fabricate new reactor fuel.

However, the commercial reprocessing plants that are currently in operation or planned to be commissioned have a total production capability of no more than 4000 tonnes of LWR spent fuel per year and their actual capacity is likely to be somewhat lower. Therefore, a massive increase of reprocessing capacity would need to be built in order to separate and eventually recycle RepU on large scale.

3. Management options and industrial experience

There are two options for the management of reprocessed uranium. Similar to other recyclable materials it may be either recycled or disposed of in a final repository. Although long-term storage, the option adopted in most cases today, is only an interim measure that allows postponing final decision, most inventories of reprocessed uranium are kept in interim storage until their owners decide on recycling or disposal.

RepU can be stored for extended periods of time in a safe and reliable manner ensuring its isolation from the biosphere and adequate protection of humans and the environment. The approach adopted for interim storage aims at avoiding irretrievability to guarantee that RepU may be either recycled or disposed of eventually.

Although the conversion of RepU into solid oxide forms to facilitate its storage is not the best solution from the viewpoint of eventual recycling, it provides a satisfactory interim solution until the industrial and economic conditions will make recycling viable. Direct conversion into UF_6 is preferable when immediate recycling into reactor fuel is envisaged.

The technologies for recycling RepU have been demonstrated and proven at significant scale although only limited quantities of this material have been recycled in fuel for reactors currently in operation. RepU has been recycled at industrial scale in several countries including Belgium, Germany, France, Japan, The Netherlands, Sweden and Switzerland and, outside OECD, India and Russia.

In the United Kingdom, over 15 000 tonnes of RepU from Magnox fuel reprocessing have been recycled in AGRs after conversion and re-enrichment in the Capenhurst gaseous diffusion plant in the early 1980s. The fuel fabricated with RepU from Magnox formed the bulk of the initial core of many of the AGRs in operation in the country. The feedback from operating experience with this fuel was very good.

In Belgium, the Doel-1 reactor has operated for a number of years exclusively with fuel derived from re-enriching RepU. In Switzerland, RepU is used since the year 2000 as blend stock, re-enriched by blending it with medium (MEU) or highly enriched uranium (HEU), a service offered by Russia on a commercial basis. Other European countries such as Germany and the Netherlands have followed the same route for recycling RepU. In Sweden, 136 tonnes of RepU have been re-enriched and recycled into LWR fuel in 2000 and 2001. India has recycled RepU into Pressurized Heavy Water Reactors (PHWR).

The use of RepU as blend stock when down-blending MEU or HEU has proven to be an extremely effective and efficient use of this material. This route avoids the drawbacks associated with the physical re-enrichment of RepU. It could be further deployed to manage ex-military HEU declared surplus to national security by Russia and the United States.

4. Issues, challenges and opportunities

Technical issues raised by the recycling of RepU are by no means major but deserve some attention owing to undesirable isotopes contained in spent fuel and transferred to the RepU stream. The typical composition of RepU derived from spent LWR fuel includes, in addition to ^{238}U, ^{232}U (0.1 to 0.3 ppm), ^{234}U (0.01 to 0.03%), ^{235}U (0.5 to 1.0%), and ^{236}U (0.4 to 0.7%). The stream of RepU issued from reprocessing plants of current generation also contains ^{208}Tl. The disposal option is unlikely to raise any significant issue for RepU beyond the challenge of building a repository, which applies to all radioactive materials.

Most of the uranium isotopes contained in RepU are alpha emitters with long half-lives raising no more demand from the radiation protection viewpoint than natural uranium. Their chemical toxicity outweighs the potential radioactive hazard associated with their handling in fuel cycle facilities. However, the presence of ^{208}Tl, ^{232}U and ^{234}U, even in very small quantities, imposes specific radiation protection measures during the storage, conversion, re-enrichment and re-fabrication steps.

Regarding the value of RepU re-use, some allowance needs to be made for the negative reactivity effect of ^{236}U, which is a neutron absorber, when fabricating new fuel. Compared with natural uranium feed, about 1.5% more RepU needs to be fed to the enrichment process, requiring about 2.5% more separative work units (SWU) to be expended to produce the same reactor worth of fuel [2]. Previous NEA studies suggest that, taking into account the various drawbacks of RepU, its economic value may range between 50 to 80% of the value of natural uranium [4].

Techniques that have been developed and used industrially in Russia for blending RepU with medium or highly enriched uranium overcome the drawbacks associated with its re-enrichment in facilities designed for natural uranium enrichment [3]. This option may provide attractive opportunities in the

framework of dismantling of nuclear warheads declared excess to national security by Russia and the United States and further agreements that might be signed on nuclear weapon elimination.

Two enrichment plants, using the gaseous centrifugation process, have re-enriched RepU uranium industrially so far: one in The Netherlands and the other in Russia. Eight fuel fabrication plants are or have been licensed to re-fabricate fuel using RepU. The experience acquired at industrial scale from those facilities provides significant and valuable feedback for a broader commercial deployment of recycling RepU.

The industrial development of RepU recycling, if this route were to be adopted broadly, would require significant efforts for building adequate industrial infrastructure for processing RepU up to its introduction into nuclear fuel. The main issue in this regard will be to identify the potential market and adapt fuel cycle facilities to the expected demand as well as to find investors for financing those facilities.

Advanced fuel cycles under development may offer opportunities for optimising the overall use of fissile and fertile materials, including RepU, in a global perspective. The ongoing R&D efforts, often undertaken in an international bi- or multi-lateral framework, benefit from holistic approaches aiming at enhancing the performance of the nuclear energy chain from the technical, economic and resource management viewpoints. In this context, closed fuel cycles allowing the recycling of fissile and fertile materials generally are considered more attractive than options leading to the discarding of potentially valuable energy sources.

Building infrastructure for the management of RepU might be difficult at the national level especially in countries where the NPP fleet is rather small. International cooperation could help providing economically viable solutions that would optimise on a global level the management of recyclable materials.

Furthermore, international cooperation from the R&D to the industrial development stages offers opportunities to share expenses and results, thereby reducing the burden borne by each country, and to address key issues such as nuclear safety, security of fuel supply and proliferation resistance in a comprehensive, holistic manner.

5. Concluding remarks

Although re-use of RepU has not been widely spread at the commercial scale yet, the technologies for its recycling have been demonstrated in several countries and the feedback from experience is satisfactory. Like for any option in the nuclear fuel cycle, the deployment of reprocessing and re-use of RepU will depend on a number of technical, economic and policy factors, including the rate of growth of nuclear power capacity and the evolution of uranium prices and fuel cycle service costs.

The management of RepU, similarly to most steps of the nuclear fuel cycle, raises a number of technical, industrial and policy issues that may be addressed better through international cooperation than on a purely national basis. Intergovernmental organisations such as the NEA and the IAEA have a key role to play in facilitating exchange of information and viewpoints between member countries aiming at strengthening cooperation for the development and the implementation of optimised options in a global perspective.

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STORAGE, PACKAGING AND TRANSPORT OF RepU

(Session 2)

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Key aspects of transporting reprocessed UF6

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Abstract. This paper considers and compares some of the key aspects and differences associated with transporting reprocessed feed and enriched reprocessed product in the form of UF_6. It introduces the general properties of UF_6, focusing on how the 'UF_6 process' currently interfaces with its neighbouring facilities within the fuel cycle. Furthermore, the paper discusses the four key methods of IAEA regulatory control which applies to the transport of UF_6, comparing the differences in how these requirements apply to virgin and reprocessed UF_6. The consequences resulting from the presence of the synthetic radionuclides found in reprocessed uranium (RepU) are considered. The importance of 'timing' is addressed, both through the conversion, enrichment, re-conversion and fuel fabrication processes and during transport. The paper considers the expected waste generation at all the above facilities and how it might be minimized or dealt with. In this context this paper identifies and discusses problems resulting from the reprocessed cylinder heel, its transport requirements and limitations. The paper also directly compares the ASTM Specifications C787 & C996 with the IAEA transport regulations identifying how well they interface. It describe how IAEA transport package requirements can be influenced by the chemical form of the material, for example, the package type differences of reprocessed UO_2 versus reprocessed UF_6 at the same specification.

1. Introduction

Reprocessed uranium (RepU) is increasingly being used for the fabrication of nuclear fuel elements. This entails the chemical separation of the uranium isotopes, conversion to uranium hexafluoride (UF_6), re-enrichment, re-conversion to uranium dioxide (UO_2) and fuel fabrication. Since many of these processes take place at different locations, transport of RepU in various forms will be necessary.

The different isotopic composition of RepU coupled with the presence of other impurities results in the need for a more considered assessment prior to transport. This is why this paper focuses on the issues surrounding the transport of reprocessed UF_6. It is worth noting that uranium in the form of UF_6 is a commodity which is shipped in substantial quantities throughout the world each year.

2. Enriching reprocessed UF6

The specifications for the finished reprocessed UF_6 product is largely determined by two parameters:

- meeting the relevant ASTM specifications; and
- the processes used for re-enrichment, or the blending process to produce enriched reprocessed uranium (ERU).

The two current methods that exist include:

- the down blending with highly enriched uranium (HEU), a method which seems likely to end in a few years due to limited supplies; and
- the conversion of reprocessed UO_3 or U_3O_8 and producing reprocessed UF_6 feed for enrichment.

In the centrifuge process all uranium isotopes except ^{238}U are enriched together with ^{235}U. The lighter isotopes ^{232}U and ^{234}U all reach the top of the cascade and are more enriched than ^{235}U. Approximately two thirds of the ^{236}U reach the top of the cascade, hence ^{236}U is slightly less enriched than ^{235}U.

3. Synthetic radionuclides

There are several new uranium isotopes, fission products and transuranics present in the fuel after irradiation:

- The decay products of the ^{235}U and ^{238}U isotopes are not very strong radiation emitters and they are short-lived; and
- It is the daughters of ^{232}U and ^{236}U which cause the most significant radiological problems. The decay chain of ^{232}U goes through three nuclides that emit intense beta and gamma radiation, namely ^{212}Pb, ^{212}Bi and ^{208}Tl, with the latter giving off a particularly strong gamma radiation.

4. The trouble with daughters

The radioactivity of ERU in form of UF_6 is higher than that of enriched natural uranium (ENU). This is why the processing of RepU can require dedicated processing facilities, including additional shielding to protect operators against radiation.

There may also be the need to provide robust management controls to avoid the cross contamination between a RepU process stream and a natural uranium process stream.

At the stage of chemical separation 'cylinder fill' of reprocessed UF_6, strong gamma daughter nuclides begin growing in. ^{232}U has a rapid decay into its primary daughter ^{228}Th, as the thorium begins to grow in and ^{208}Tl increases in the same proportion. It is the ^{208}Tl which emits high energy gamma rays (see Section 3.).

On evacuating the UF_6, these daughters become concentrated in the heel. Thus, interestingly each stage of chemical separation, meaning 'cylinder emptying' and 'cylinder fill', also results in a purification of the UF_6. This can be used as a complimentary process for further purification before enrichment and fuel fabrication.

Unfortunately, this purification has a major drawback, as it generates a waste residue of concentrated daughters giving off high radiation levels for many years. This waste then requires careful management to reduce its long- and short-term impact on operators and the environment.

5. Dose comparison - Heeled reprocessed UF_6 cylinders

On emptying the cylinder, the UF_6 is evacuated leaving anything which is not UF_6 remaining in the cylinder heel ('heeled cylinder'). This results in a concentration in the strong gamma daughters and a mixture of radionuclides which will typically fail the LSA-II criterion. They would have a high specific activity (activity per gram). This gamma dose also increases significantly with time.

The enrichment process gives rise to higher levels of ^{232}U in product cylinders, hence the overall dose effects becoming even worse.

Figure 1 provides typical information on the surface dose rates found in both full cylinders containing reprocessed UF_6 and in heeled cylinders. It also clearly demonstrates the effect of ageing and the 'growing in' of the gamma daughters.

6. Timing is everything

The clock starts ticking on cylinder fill, as the gamma daughters begin to form, increasing in radiation levels for around a decade.

On evacuating the product UF_6 into the conversion plant the process starts again. The daughters begin forming in the uranium powder, with the ^{208}Tl gamma dose gradually increasing throughout both the sintering and the fuel fabrication process.

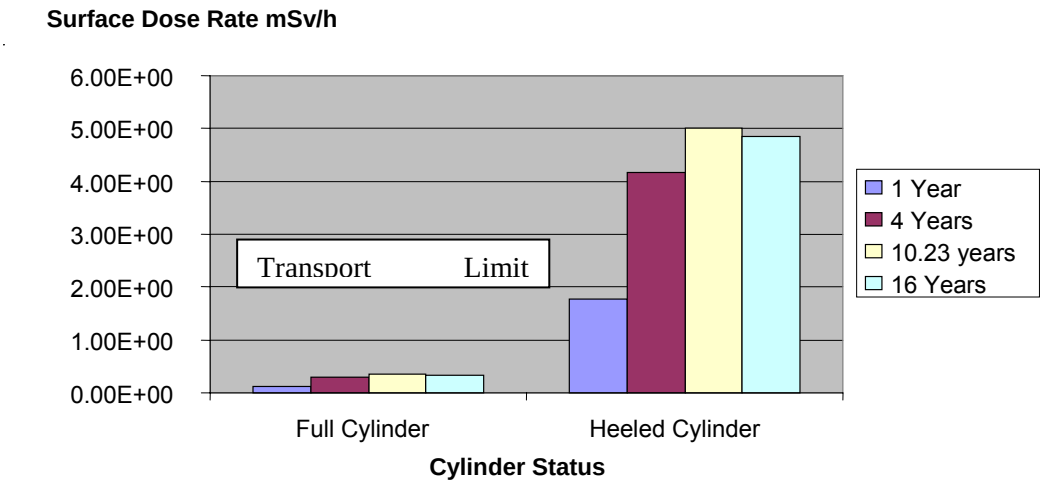

FIG. 1. Surface dose rate in full cylinders containing reprocessed UF6 and heeled cylinders.

There are typically heightened levels of ^{234}U as a result of enriching RepU by centrifuges. This ^{234}U has a strong alpha emission with a moderate half-life, giving further personal protection issues during processing.

Controlling the dose to operators need be managed by either automation and/or shielded/contained facilities, and the dose may be reduced by restricting the time after chemical separation.

7. ASTM product specifications

The key ASTM product specifications for UF_6 are:

- C787 'Standard Specification for Uranium Hexafluoride for Enrichment'; and
- C996 'Standard Specification for Uranium Hexafluoride Enriched to Less Than 5% ^{235}U'.

These specifications define the acceptable nuclide levels in RepU and ERU, respectively. Although these limits specifically apply to UF_6, the limits are often used as a reference in the specification of RepU in other forms.

Although the ASTM standards for reprocessed UF_6 are not the only ones that exist they are the most commonly used throughout the nuclear industry.

Figure 2 demonstrates the key differences between natural and reprocessed feed and product specifications. According to this Figure, the most striking markers are ^{232}U and ^{236}U. Please note the logarithmic scale on the Y axis.

8. The IAEA specifications

In comparison, the IAEA Transport Regulations provide for four key protection elements controlling the areas of activity, radiation, criticality and robust mechanical testing.

9. ASTM vs IAEA

There is a crossover point when considering both the ASTM specifications and the IAEA requirements.

The 'A2' is an IAEA transport 'hazard rating' for the mixture of radionuclides present in the reprocessed UF_6. The lower the value the higher is the hazard.

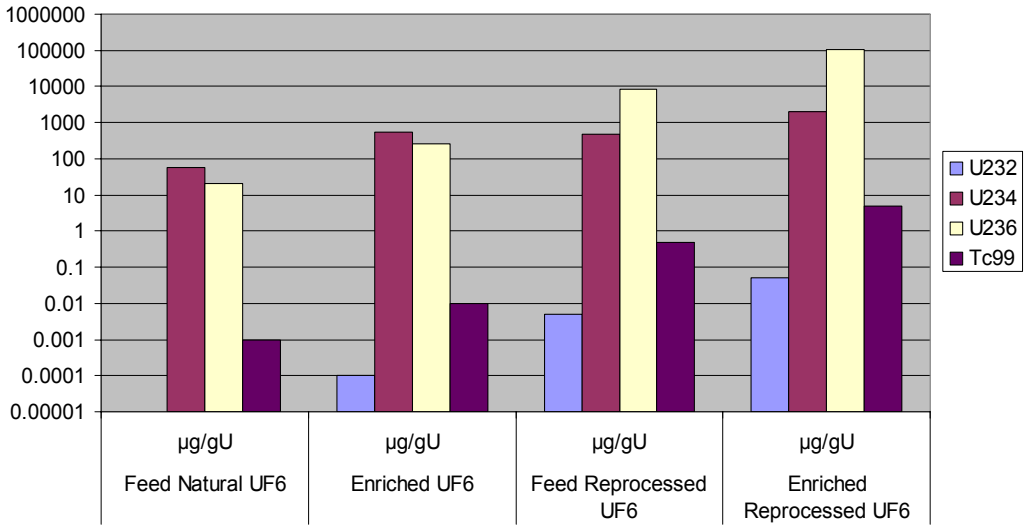

FIG. 2. Key differences between natural and reprocessed feed and product specifications.

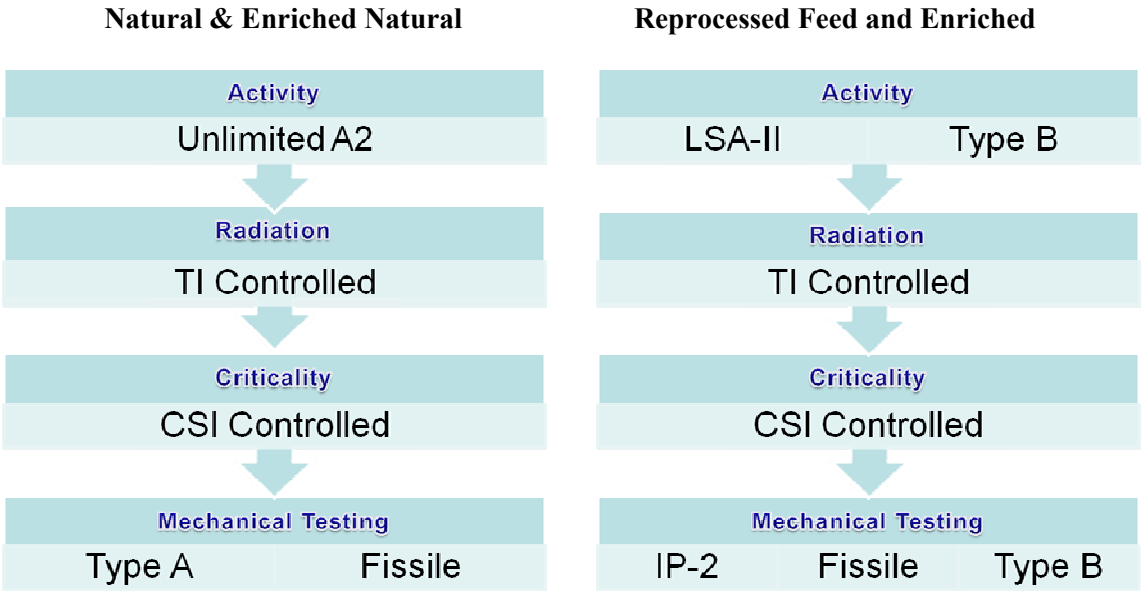

FIG. 3. Key protection elements for activity, radiation, criticality and mechanical testing according to IAEA transport regulations.

UF_6 derived from fresh (unirradiated) uranium is granted an unlimited A2 value (low hazard), whereas reprocessed UF_6 will have an absolute value dependant on its radionuclide constituents.

UF_6 derived from uranium separated from spent fuel through reprocessing can contain other nuclides in varying concentrations:

- Uranics, such as ^{232}U, ^{234}U, ^{235}U, ^{236}U, ^{237}U and ^{238}U.
- Transuranics, such as ^{237}Np and ^{239}Pu.
- Fission products, such as ^{106}Ru, ^{95}Zr, ^{95}Nb and ^{99}Tc.
- Daughter products, such as ^{223}Pa, ^{228}Th and ^{208}Tl.

The current transport infrastructure and packaging used to transport both natural and reprocessed UF_6 is carried out in Industrial Packaging IP-2 or Type A packaging. To use this packaging type the reprocessed UF_6 must meet a certain criterion known as LSA-II. It is defined as material in which the activity is distributed throughout and the estimated average specific activity does not exceed 10E-4 A2/g for solids.

Hereafter this paper makes a comparison by taking the ASTM limits and running them through the LSA-II criterion check (Table 1).

When calculating the A2 value for the mixture of nuclides, it is necessary to take account of the ageing of ^{232}U and of the growing in of ^{228}Th which reaches a maximum after around 10 years. This is accounted for by assuming that the ^{228}Th is in full equilibrium with ^{232}U to give the maximum figure.

Trace quantities of radioactive impurities, such as fission products and transuranics, are present in RepU. According to the author's experience and of that laid down in previous publications, these impurities have a negligible impact on meeting the LSA-II specification. It is vital that they are taken into account in the calculation, their impact quantified and then neglected as applicable.

Even taking the worst case ASTM specification for enriched reprocessed UF6, it was discovered that this material still meets the LSA-II criterion.

There were two findings which were of particular interest:

- Firstly, the residual heel found in cylinders, both from RepU feed or from ERU, would typically fail to meet the LSA-II criterion. This is primarily driven by the concentration of daughters and the lack of large quantities of the relatively innocuous ^{238}U. The residual heel having a high specific activity (activity per gram) effectively makes the heel non-transportable in the current transport packaging; and
- Secondly, at the maximum ASTM specification for reprocessed UF_6 the LSA-II criterion was met. However, once the UF_6 changes its chemical and physical form into UO_2 powder, pellets, pins or fuel assemblies the LSA-II criterion is not met.

This has the potential to cause some problems as the transport infrastructure may need higher categories of packaging than the ones which are currently in service. Or, alternatively, the existing packaging safety case has to be enhanced. The calculation included at the end of this paper further demonstrates this issue. This phenomenon is due to the chemical form of the uranium having a direct impact on its hazard rating (IAEA A2 value). In the form of UF_6 the solubility of the uranium has a fast lung absorption, hence limiting the time the nuclides are present in the body. In the form of UO_2, the solubility of the uranium has a slow lung absorption and, therefore, spends longer in the body, potentially causing more harm.

10. Conclusion

Reprocessed UF_6 meeting the ASTM specifications should also satisfy the IAEA Transport Requirements. Previous studies have shown that the radiation levels of a full cylinder containing RepU are not vastly different from those of a cylinder containing natural unirradiated uranium, and these radiation levels are well within the criteria required for transport. This is most likely due to the excellent shielding properties offered by the ^{238}U.

Radiological problems associated with the handling of RepU are clearly an issue, causing most issues with the more human-intensive operations, such as fuel fabrication. ^{232}U and its high gamma daughters are the main radiological enemy. Heightened levels of ^{234}U are causing further difficulties through airborne alpha. These human factors can be managed by providing automated or dedicated processing facilities. Purification through chemical separation and careful timing can also be used to great advantage.

TABLE 1. ASTM SPECIFICATIONS AND LS-II CRITERION FOR ENRICHED REPROCESSED UF_6 AND ENRICHED REPROCESSED POWDER

ASTM ENRICHED REPROCESSED UF_6

		Density of Activity (Bq/gU)	Fraction of Activity (f(i))	A2 (Bq) (X(i))	f(i)/X(i)	% Effect on A2 Value	µg/gU	g/gU	Specific Activity (Bq/g)	Specific Activity (TBq/g)	A2 (TBq)
Uranium	^{232}U2	4.14E+04	5.08E-02	1.00E+10	5.08E-12	8.17%	0.05	5.00E-08	8.28E+11	8.28E-01	1.00E-02
Isotopes	^{234}U	4.62E+05	5.67E-01	9.00E+10	6.29E-12	10.13%	2000	2.00E-03	2.31E+08	2.31E-04	9.00E-02
	^{235}U	4.00E+03	4.91E-03	Unlimited	0.00E+00	0.00%	50 000	5.00E-02	8.00E+04	8.00E-08	Unlimited
	^{236}U	2.52E+05	3.09E-01	Unlimited	0.00E+00	0.00%	10 5000	1.05E-01	2.40E+06	2.40E-06	Unlimited
	^{238}U	1.18E+04	1.44E-02	Unlimited	0.00E+00	0.00%	94 5000	9.45E-01	1.24E+04	1.24E-08	Unlimited
Daughters	^{228}Th	4.14E+04	5.08E-02	1.00E+09	5.08E-11	81.70%		0.00E+00	3.04E+13	3.04E+01	1.00E-03
	^{99}Tc	3.14E+03	3.85E-03	9.00E+11	4.28E-15	0.01%	5	5.00E-06	6.28E+08	6.28E-04	9.00E-01
	Total	**8.15E+05**	**1.00E+00**		**6.22E-11**	**100.00%**					
				A2 =	**1.61E+10**						
Activity Bq/g of UF_6		5.51E+05						g per A2	29 191.94		
			LSA-II Criterion 1E-04		**1.61E+06**	**PASS**					

ASTM ENRICHED REPROCESSED POWDER

		Density of Activity (Bq/gU)	Fraction of Activity (f(i))	A2 (Bq) (X(i))	f(i)/X(i)	% Effect on A2 Value	µg/gU	g/gU	Specific Activity (Bq/g)	Specific Activity (TBq/g)	A2 (TBq)
Uranium	^{232}U	4.14E+04	5.08E-02	1.00E+09	5.08E-11	20.52%	0.05	5.00E-08	8.28E+11	8.28E-01	1.00E-03
Isotopes	^{234}U	4.62E+05	5.67E-01	6.00E+09	9.44E-11	38.16%	2000	2.00E-03	2.31E+08	2.31E-04	6.00E-03
	^{235}U	4.00E+03	4.91E-03	Unlimited	0.00E+00	0.00%	50 000	5.00E-02	8.00E+04	8.00E-08	Unlimited
	^{236}U	2.52E+05	3.09E-01	6.00E+09	5.15E-11	20.80%	10 5000	1.05E-01	2.40E+06	2.40E-06	6.00E-03
	^{238}U	1.18E+04	1.44E-02	Unlimited	0.00E+00	0.00%	94 5000	9.45E-01	1.24E+04	1.24E-08	Unlimited
Daughters	^{228}Th	4.14E+04	5.08E-02	1.00E+09	5.08E-11	20.52%		0.00E+00	3.04E+13	3.04E+01	1.00E-03
	^{99}Tc	3.14E+03	3.85E-03	9.00E+11	4.28E-15	0.00%	5	5.00E-06	6.28E+08	6.28E-04	9.00E-01
	Total	**8.15E+05**	**1.00E+00**		**2.47E-10**	**100.00%**					
				A2 =	**4.04E+09**						
Activity Bq/g of UO_2		7.18E+05						g per A2	5627.04		
			LSA-II Criterion 1E-04		**4.04E+05**	**FAIL**					

One of the major drawbacks of using RepU is the residual ‘waste’ heel generated from emptying a feed cylinder at the enrichment facility and emptying the product cylinder at the reconversion/fuel fabrication facility. The heel cannot be easily transported, has concentrated aggressive daughters and requires a long-term waste management strategy.

Changing the chemical form of the RepU from UF_6 to UO_2 can have a significant impact on the LSA-II acceptance criterion. This may bring into question the suitability of the existing transport packaging, demanding a review and even modification to respective safety cases currently used for shipping un-irradiated powder, pellets and fuel elements.

REFERENCES

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[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Interim Guidance for Safe Transport of Reprocessed Uranium, IAEA TECDOC–750, IAEA, Vienna (2004).

Cost effective transport of industrial fissile packages by sea

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Abstract. Sellafield Limited provides a storage service to its customers for uranium products in the form of UO_3. This service is not indefinite so at some point the UO_3 requires exporting. The UO_3 to be exported has a range of ^{235}U enrichments, some of which meet the IAEA Fissile Excepted Package criteria and some that are marginally outside this criterion. Therefore, this implies that two package types will be required: a Fissile Excepted package and a Fissile package. This latter will require approval by the Competent Authority. The challenge is to minimize the number of shipments by optimizing a single package design and the loading arrangement of this design to enable the safe transportation of large volumes of the fissile UO_3 material. To accommodate the higher enriched material the use of an Industrial Fissile (IF) package is proposed. IF packages are typically IP-2 qualified packages supported by a criticality safety case. This safety case demonstrates an adequate sub-critical safety margin, without claiming any integrity for the packaging, under accident conditions of transport. This option provides the potential for significant cost savings, particularly with respect to package testing, as the safety of the package needs only be demonstrated for normal conditions of transport. For this specific application research was carried out to establish an acceptable method for: mixing UO_3 over a range of fissile enrichments; maximizing payload within the package; maximizing the number of packages on the trains; and maximizing the number of packages on the vessels to minimize shipments. The approach adopted is somewhat complex requiring both an IAEA Shipment Approval and IAEA Radiological Protection Programme (RPP) for 'special use vessels'. There has been a great deal of constructive interaction between the plants involved, criticality specialists, project engineers and the United Kingdom (UK) Competent Authority during the development of this approach. A systematic set of controls has been developed to ensure compliance with IAEA regulations during loading operations and transport which will minimize shipments without compromising safety.

1. Introduction

The Thermal Oxide Reprocessing Plant (Thorp) at Sellafield in Cumbria reprocesses irradiated oxide fuel from the advanced gas-cooled reactors (AGR) and from light water reactors (LWR). Uranium and plutonium, which are available to be recycled, make up 97% by weight of the irradiated fuel. The remaining 3% is made up of fission by-products.

Under current contracts all of the Japanese fuel delivered to Sellafield has now been reprocessed and the resulting quantity of UO_3 with ^{235}U enrichment up to 1.24% (in excess of 2000 tU) has been made available to the Japanese customers and is presently stored in the Thorp UO_3 Store at Sellafield.

The proposed export of this UO_3 must satisfy the relevant IAEA transport regulations, which places significant controls on the transport of fissile material that are over specific thresholds, in this case ^{235}U enrichment. A key challenge for the transporter is that UO_3 made available to Japanese customers is at a range of enrichments greater than 0.711 % ^{235}U and is split between the threshold for a fissile package and for a fissile excepted package. Using a traditional approach to compliance with the transport regulations would subject the project to a vast number of shipments due to wasted space both within the package and on the conveyances.

A project was established in late 2004 with the objective to deliver an IAEA compliant cost effective solution for the export of enriched UO_3 in both the fissile category and the fissile excepted category. This will enable Sellafield Limited to support individual Japanese customers in their plans to export

their enriched UO_3 from the Thorp UO_3 Store to Russia for eventual recycle of that material back into nuclear fuel.

This paper demonstrates the use of the Industrial Fissile Package category and a novel approach to optimisation of international shipments.

2. Regulations for UO_3 (in excess of natural ^{235}U enrichment)

UO_3 contains relatively low specific activity for each of the radionuclide present in the fingerprint and commonly meets the LSA-II criteria (226b of Reference 1, hereinafter referred to as TS-R-1). This category of material requires packaging meeting the IP-2 criteria (TS-R-1 Table 4 [1]).

The Thorp UO_3 is enriched in ^{235}U above natural (0.711% ^{235}U). Therefore, in respect of the transport regulations this UO_3 is classed as Fissile material and requires a package meeting the Fissile Package requirements (TS-R-1 paragraph 671 [1]). The IAEA has recognized that not all material meeting the IAEA TS-R-1 definition for fissile material classification presents a criticality risk and this criteria (Exceptions from the requirements for packages containing fissile material) is found in paragraph 672 (TS-R-1 [1]). 60% of the Thorp UO_3 falls into paragraph 672b, and is therefore Fissile Excepted, but the remaining 40% requires the use of a Fissile Package.

3. Regulations for fissile packages

Various categories of packages can be used to transport nuclear fuel cycle materials, such as enriched uranium hexafluoride, uranium dioxide, fresh fuel and also spent fuel, all of which are capable of sustaining a nuclear chain reaction.

Depending upon the nature and quantities of materials involved, Industrial, Type A, Type B(U) and Type B(M) packages are used for surface transport and the high integrity Type C package for air transport. Packages are classified as Fissile Packages when they are designed to carry fissile material and they are then categorized as IF, AF, B(U)F, B(M)F and CF. Note that IF designs are not a commonly used/accepted package type.

The regulations require that the criticality safety of a package used to transport fissile material is demonstrated during routine, normal and hypothetical accident conditions of transport. This is generally achieved by demonstrating integrity against a series of onerous and costly performance tests. As mentioned above, the use of an IF-package is identified as an option for this project. This package type gives significant advantages over other fissile package types as IF applications use calculations to demonstrate adequate sub-critical safety margins without claiming any integrity for the packaging under accident conditions of transport. Thus, IF designs are significantly less costly to develop, test and manufacture.

4. The development of a fissile package

Initial planning for transport within the UK was based on the use of an overpack to be applied to each drum of UO_3. However, this approach was not cost effective for overseas transports. A Value Management Study was carried out in 2004, which had the objective of identifying a more cost effective fit for purpose solution. The identified solution was to export the fissile UO_3 using a specially designed Industrial Fissile package based on a full height International Standard Organization (ISO) freight design. This design would have the potential to be utilized in transporting all Thorp UO_3 regardless of enrichment (up to and including the identified maximum of 1.24% ^{235}U) or destination. It was concluded that whilst this was a novel approach and would be viewed as such by the Competent Authorities, International Nuclear Services had the necessary experience with IF applications to be able to successfully develop this design and achieve UK Competent Authority approval and Russian Competent Authority Validation. The IF-package project was designated unique design number IF-96 3573.

5. Development of the IF-96 3573 package concept and parameters

The package will comprise a full height ISO freight container (Design No. 3573). This container is required to have a single end opening door that can wrap around and latch to the side of the container.

The package must be designed with a specific internal load restraint system that will be used to secure the pallets containing drums of UO_3. The internal load restraint system is to be designed to provide safe transport for the laden pallets under normal conditions of transport.

The gross mass of the loaded ISO is to be restricted to 20 tonnes due to handling restrictions at some international ports.

6. Regulatory requirements for the IF-96 3573 design

The regulations for IF-packages are subjective and therefore open to interpretation. From past experience with IF packages it was clear that the design and the concept had to be agreed with the UK Competent Authority ahead of any project commitment.

As well as the general regulatory requirements for all package designs, the regulations specific to this IF-96 3573 design can be split into three sub sections:

- IP-2 Package requirements (TS-R-1 paragraph 606-616, 681-622 [1]);
- Criticality requirements (TS-R-1 paragraph 681 [1]); and
- Normal Conditions of Transport requirements (TS-R-1 paragraph 719-724 [1]).

6.1. IP-2 package requirements

IP-2 packages must be designed such that they can demonstrate containment under Normal Conditions of Transport (NCT). In the regulatory spirit this is demonstrated by subjecting the package to both a free drop test and a stacking test. There are a number of alternative requirements (TS-R-1 paragraph 624 - 628 [1]) which, if satisfied, remove the need to subject the designs to additional testing to demonstrate integrity to the same criteria (NCT). The 3573 package has been designed to carry Thorp UO_3 in solid form and is taking advantage of these alternative requirements which were introduced by the IAEA's 1985 Safety Series No. 6 regulations [5] and remain in current regulations (TS-R-1 paragraph 627).

Experience shows that paragraph 627 can be interpreted inconsistently. For this reason the UK Competent Authority has issued further guidance against this paragraph [2 & 3] and the UK industry has been following such guidance by subjecting all IP-2 freight containers to leak tests before, during and after specific ISO 1496/1 type tests [4].

6.2. Criticality requirements

The regulations require a criticality assessment of a single isolated package (TS-R-1 paragraph 677 [1]). As no claim is made for water tightness of the ISO it is must be assumed that water can leak into the ISO to any extent and also assumed that the package and drums have lost their integrity, allowing the UO_3 powder to assume the most reactive geometry.

As IP-2 packages are not required to demonstrate containment under accident conditions of transport it will be necessary to consider the state of the packages post the NCT tests (TS-R-1 paragraph 681a,b [1]). The "water spray" NCT test will not need to be performed nor assumed to affect criticality calculations as the package is made from steel and is designed to prevent ingress of water under NCT and this test would occur before the impact test under the IAEA approved sequence.

In respect of accident conditions of transport, the IAEA regulations require an assessment of an array of damaged packages (TS-R-1 paragraph 682 [1]). No claim is made for the package integrity under

accident conditions. Therefore, it will be appropriate to assume that the fissile material in a group of packages is entirely free to combine and assume the most reactive configuration, with ingress of water.

Finally, for a criticality safety control on conveyances, the regulations require the calculation of a Criticality Safety Index (CSI) for a Group of Packages (TS-R1 paragraph 528, 530, 569 [1]).

6.3. Normal Conditions of Transport requirements

Again, Industrial Fissile Packages do not entirely fit within the general criteria for either IP-2 packages or Fissile Packages. Even though the NCT tests are the criteria to which the alternative arrangements are compared to demonstrate safety equivalence, the Competent Authorities will not accept these tests for demonstrating containment when criticality safety cases rely on the package maintaining containment under NCT. Therefore, for IF packages designed to comply with either of the alternative requirements TS-R-1 paragraph 624-628 [1]) they must also demonstrate containment post an impact test from the appropriate drop height.

7. Design, manufacture prototype and test the IF-96 3573

The 3573 package has been designed and is currently in manufacture. The key features of the design can be seen from Figure 1 below. The design comprises of a specially designed full height ISO freight container fitted with a single door, high efficiency particulate air-filter (HEPA filter) and an internal restraint system.

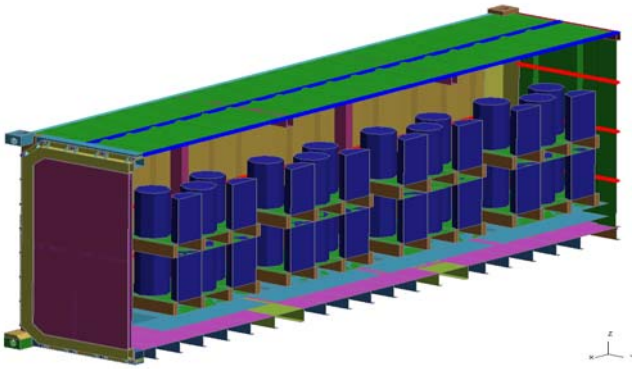

FIG. 1. 3D illustration of the 3573 IF-96 design courtesy of Nexia Solutions UK.

Testing will be carried out in compliance with the DfT Guidance [3] which insists on additional leak testing under side wall loading, end wall loading, longitudinal racking and transverse racking tests from the ISO 1496/1 Type tests [4].

7.1. Impact testing

The prototype will not be subjected to any impact testing. Finite element analysis (FEA) has been carried out to demonstrate containment integrity post impact testing. Again, this IF-96 3573 design reveals another interpretation issue within the regulations, this time with Table 8 of TS-R-1 free drop distance for testing packages against NCT tests. This design is required to transport between 1 and 64 drums, therefore the gross weight could potentially vary over 3, out of the 4 thresholds, in Table 13 of TS-R-1 [1] which denote different free drop heights.

Using an energy argument against the thresholds in Table 13 of TS-R-1 [1], it shows that the highest energy of all thresholds occurs with a mass of 15 tonnes dropped from 0.6 meters (88.29 kJ). Therefore, modeling this drop provides us with a bounding case to enable the design to comply with the regulations and operate the package across the varying gross weights from >5 to <20 tonnes.

The FEA modeled the 3573 as if three lifting points had failed simultaneously dropping the container onto the door corner edge from 0.6 meters. This demonstrated a worst case orientation within the spirit of NCT tests and the results revealed minimal plastic set deformation, and no loss of containment.

8. Package criticality safety case

IAEA transport regulations always require a worst case scenario assessments. Therefore, the 3573 criticality safety case was based on optimized spheres of UO_3 and close fitting reflectors, and no credit was taken for the increased neutron leakage and thermal neutron absorption that would result from transporting the UO_3 in primary drums and the 3573 ISO container.

The UO_3 powder bounded by this safety case is that with enrichments from 1% to 1.24% ^{235}U. To both simplify the assessment and for convenience of the export operation 23 enrichment bands were chosen and safe masses of ^{235}U were calculated at the upper boundary value.

These shipments are to take place under exclusive use. This allows a relaxation in the regulations in respect of “Fissile Package Grouping” for criticality safety.

“Fissile Package Grouping” - the regulations place restrictions on the stowage during transit of fissile packages. Each group of packages, where the sum of criticality safety indexes totals 50, must be spaced from any other such groups by a distance of a 6 meters envelope (TS-R-1 paragraph 569, 570 [1]).

It is permitted by IAEA to increase the CSI per group of packages to 100 (TS-R-1 paragraph 571) [1] providing exclusive use can be claimed.

The results of the assessment gave indicative working limits for safe masses of ^{235}U per enrichment band for a group of fissile packages in that band. This could be equated to a safe mass of UO_3 per group, furthermore to numbers of UO_3 drums at that enrichment band per 3573 package.

This analysis revealed that 3573 packages containing UO_3 in enrichment bands over approx 1.15% ^{235}U would not be fully loaded (example <20 drums total for 1.24% ^{235}U compared with a possible 64 drum capacity), meaning that one individual package in that enrichment band would be designated with a CSI of 100 (the safe mass). The regulations permit this approach providing a Shipment Approval is obtained from the Competent Authority (TS-R-1 paragraph 820c [1]).

It should be noted that to satisfy the requirements of the Shipment Approval, in addition to the general requirements of a Package Design Safety Report (PDSR), a complete review of the entire shipment/transport process must be completed to demonstrate an adequate level of control at all stages.

However, even with a CSI for the group at 100 and, where necessary, an individual package with a CSI of 100, a vast number of packages and voyages would have been required. So, further investigations were completed to maximize the volume of UO_3 able to be transported in any one shipment.

9. Assessment of optimization of payloads for packages

In the introduction of this paper it was noted that Sellafield Limited customers also own UO_3 with enrichments below 1% ^{235}U. This is transported in fissile excepted packages, overpacked in General Purpose Freight Containers to assist international handling. There appeared to be an opportunity to use these freight containers filled with UO_3 enriched to <1% ^{235}U and the individual drums to:

- fill the 6 meters spaces between groups for the rail and sea journey, and/or
- to mix load the 3573 package with both <1% and >1% up to 1.24 % ^{235}U enriched UO_3.

This was termed “group infill” and “package infill”.

Group infill

This concept refers to filling the 6 meters spacing between packages with general purpose freight containers loaded with UO_3 <1% ^{235}U (fissile excepted packages).

Package infill

As explained above, for enrichments >1.15% ^{235}U the 3573 package will be part loaded and the remaining space is potentially wasted within the package. It is proposed to fill this space with drums of UO_3 <1% ^{235}U enrichment. Therefore, a new set of fissile limits was generated for use with package infill.

10. Assessment of optimization of number of voyages required for export

By demonstrating that the vessel fully loaded with enriched UO_3 (> natural and up to 1.24% ^{235}U) maintains an adequate sub-critical safety margin under hypothetical accident scenarios, the vessel can be exempted from taking account of the CSI and the mandatory 6 meter spaces between groups of 100 CSI. This allows the vessel cargo space to be completely optimised, hence reducing the number of voyages required. This concept is known as a Special Use Vessel (TS-R-1 paragraph 576 [1]).

The regulations demand that the flagstate of the vessel approves this assessment as a part of a Radiological Protection Programme (RPP) for the vessel. In this instance the general RPP must be supplemented with this vessel criticality safety case and shielding assessment, to enable the ship to claim Special Use Vessel. Note that for the criticality assessment of the vessel the IAEA does not insist that their extremely pessimistic guidelines for accident condition assessments are followed. However, a large number of calculations covering normal and credible accident conditions (e.g. flooding, etc.) were considered and shown not to result in a criticality.

The PDSR, Shipment Approval and RPP for the Special Use Vessel will be submitted to the UK Competent Authority later this year for Approval. Russian validation is required post UK approval.

11. Conclusions

The 3573 project has identified potential new pathways through the regulations to maximise package loading efficiency and minimise voyages for international shipments of reprocessed UO_3 (fissile) without any loss or reduction in safety margins. As a result of its success so far, a significant cost saving for the recycling of enriched UO_3 has been achieved. Additionally, during this novel approach a number of regulatory interpretation issues have been identified which could benefit from further investigation by the IAEA to ensure future consistency. It is hoped that this paper will serve to inspire others to explore interpretations of the transport regulations for identifying cost saving opportunities for the transport of nuclear fuel cycle materials.

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RepU FUEL ASSEMBLY MANUFACTURING

(Session 3)

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Manufacture and operational experience of reprocessed uranium in WWER reactors

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Abstract. This paper deals with the compensation for unwanted even uranium isotopes present in reprocessed uranium (RepU) by increasing the ^{235}U enrichment level of the material. Furthermore, it presents the operational experience with enriched reprocessed uranium (ERU) fuel in the WWER-440 reactor unit Kola-2 and the WWER-1000 reactor unit Kalinin-2.

1. Introduction

Long-term operation of nuclear power reactors and the further increase of installed nuclear generating capacities contemplate the closure of the nuclear fuel cycle with the recycling of plutonium and reprocessed uranium (RepU) (in the Russian Federation also referred to as 'uranium reclaim') back into reactors. The problems associated with the recycling of RepU regained from spent nuclear fuel assemblies (SNF) back into nuclear power plants (NPP) has a long history. The recycling of RepU has to a certain degree already been implemented in individual countries. At present, the Russian Federation is one of the few countries that have industrial experience in the recycling of RepU. Since about 20 years, RepU gained from the reprocessing of spent fuel from WWER-440, BN-600, research and transport reactors is used for the fabrication of fuel for RBMK reactors [1]. A characteristic feature of RepU is that it contains - apart from the traditional isotopes ^{235}U and ^{238}U - also ^{232}U, ^{234}U and ^{236}U. ^{234}U and ^{236}U provide fuel with little neutron absorption. As a result of its radioactive decay, ^{232}U produces thallium (^{208}Tl) which emits hard rays. Operational experience of using pilot fuel assemblies containing enriched reprocessed uranium (ERU) in WWER-440 and WWER-1000 reactors allowed to substantiate the use of ERU fuel in Light Water Reactors (LWR) [2]. According to calculations, the residual ^{238}U content of spent WWER-1000 fuel is higher than that of spent enriched natural uranium (ENU) fuel with burnups of 60 MW•d/kg U [3].

When introducing RepU fuel into a reactor, the length of the individual fuel cycles of this reactor and the reloading scheme itself should be kept unchanged. That is why the neutron physical characteristics of ERU fuel assemblies should differ little from those of ENU fuel assemblies. Unlike ENU fuel, ERU fuel of the same enrichment in ^{235}U contains, as mentioned before, also ^{234}U and ^{236}U. The influence of these two uranium isotopes is seen in additional neutron absorption which adversely affects the breeding properties of fuel and which shortens the length of the fuel cycle. In order to maintain the fuel's breeding properties, the influence of ^{234}U and ^{236}U should be compensated by an increased ^{235}U content of the fuel. The problems associated with the compensation of the effects of ^{234}U and ^{236}U contained in ERU fuel for WWERs is discussed in Section 1. Results of the calculations of the compensation ratios for fuel with different equivalent enrichments and with an increased content of ^{236}U are provided.

Although the technologies applied for the production of ENU and ERU fuel are similar, the existence of even uranium isotopes and of radioactive fission products in RepU entails certain peculiarities regarding the processing of such material. Currently the Russian technologies for the fabrication of RepU powder with different ^{235}U enrichment levels comprise the hydrolyzed (solvent) extraction (ADU process), the 'dry' conversion of uranium dioxide powder and the gas flame technique. The dry conversion technique is used by OAO Mashinostroitelny Zavod (OAO MSZ) in its facilities at Elektrostal (Moscow region). The pellets are fabricated according to the standard technology. Both the powders and the pellets fully meet the normative and technical documentation requirements.

Section 3 of this paper provides analyses of experience gained with the usage of ERU fuel assemblies in the core of the WWER-440 reactor Kola-2. This reactor has been transferred to the industrial-scale operation of ERU fuel. The operation of ERU fuel assemblies in the core of the WWER-1000 reactor Kalinin-2 is given in Section 4.

2. Compensation of the ^{234}U and ^{236}U content in ERU fuel assemblies

The influence of the neutron absorption of ^{234}U and ^{236}U on the breeding properties of ERU fuel assemblies is considered in an asymptotic approximation. In order to quantify the necessary compensation of the effects of ^{234}U and ^{236}U, calculations of eternal grids of similar fuel assemblies with different ^{234}U content were performed. These calculations did not include the ^{234}U content in standard ENU fuel [4].

The compensation of the ^{236}U content by an increased ^{235}U level cannot provide the ERU fuel assembly with breeding properties which are at any time the same as those of standard ENU fuel; this is due to the gradual burnup of ^{236}U. Nevertheless, the compensation of ^{236}U ensures a minimal difference between the breeding properties of ERU and ENU fuel. The 'equivalent' enrichment of ERU fuel means the enrichment of standard ENU fuel.

To calculate the relative divergence and sensitivity ratio of the average fuel assemblies' breeding ratio per fuel cycle, fuel assembly burnup calculations have been carried out for the whole range of changes of the relative mass fraction of ^{236}U in ERU. This resulted in the dependence of the additional enrichment (over-enrichment) $\Delta^* C_{235_U}$ (needed for the compensation of ^{236}U) from the ^{236}U content in the fuel.

In practice, a more simple dependence can be used which is achieved by linear approximation of the additional (compensating) enrichment $\Delta^* C_{235_U}$ using the least-squares method:

$$\Delta^* C_{235_U} \approx K_1 \cdot C_{236_U} + K_2 \tag{1}$$

where K_1 and K_2 are compensating ratios.

The value of the compensating enrichment $\Delta^* C_{235_U}$ depends on the ^{236}U content of ERU.

In the same way the questions associated with the compensation of the ^{234}U content in ERU fuel were solved. Concerning the ^{234}U content in ERU fuel, the same formulas apply regarding the calculation of compensating ratios and of the additional (compensating) enrichment.

As stated above, ERU contains ^{234}U and ^{236}U isotopes. The content of these isotopes in fuel is compensated independently. The preciseness of this approximation is proved by calculations.

The calculation of ^{234}U and ^{236}U content compensation ratios in ERU fuel has been done for fuel rods of WWER-440 fuel assemblies with a 5-year fuel cycle and for fuel rods of WWER-1000 fuel assemblies with a 4-year fuel cycle. According to the calculations, the compensating enrichment goes up rather slowly when the equivalent enrichment of ERU fuel increases. As shown in Figure 1, after compensation the breeding properties of ERU fuel were in the first half of the fuel cycle lower than the ones of the standard ENU fuel, but they were higher in the second half of the fuel cycle. Nevertheless, practically the absolute values of the relative divergence of the breeding ratio k^r of ERU fuel from k^n of ENU fuel at the beginning and at the end of the fuel cycle differ only little.

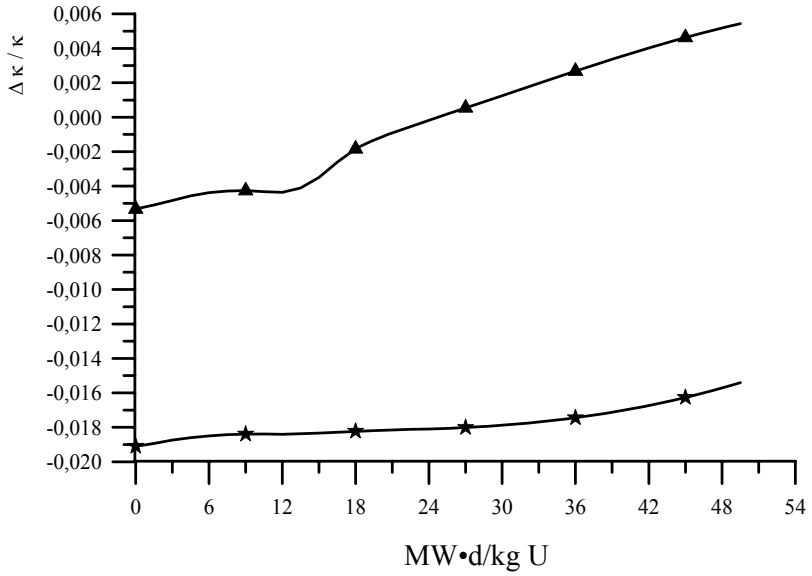

FIG. 1. Relative divergence of breeding ratio of WWER-1000 TVSA ERU fuel assembly versus burnup. ERU fuel data: 1 w/o ^{236}U; 'equivalent' enrichment 4.4% ^{235}U. ^{236}U content in ERU fuel was compensated (▲), was not compensated (✱).

When the ^{236}U content in ERU increases, the compensation ratios K_1 and K increase as well, while K_2 becomes smaller, although not significantly. This can be explained by the behaviour of the $\Delta^* C_{235_U} / C_{236_U}$ value which can be regarded as the compensation ratio with constant dependence from the ^{236}U content in the fuel. As shown in Figure 2, this value grows when the ^{236}U content in the fuel decreases. And with the ^{236}U content in the fuel going down, the compensating enrichment decreases as well (see Fig. 3).

According to analyses, the linear approximation of the compensating enrichment has the maximum error when the ^{236}U content in the fuel is on the verge of the range (meaning between 0.9 and 1% ^{236}U) (see Fig. 4). Its absolute error in the whole range (0.1-1% ^{236}U) in ERU fuel with an equivalent enrichment of 4% ^{235}U reaches 0.014 %. The relative ^{236}U mass fraction in currently fabricated fuel is in the range of 0.2~0.8% ^{236}U. The absolute error of compensation for this range is not more than 0.01%.

Also according to precise calculations the absolute error of the compensating enrichment of ERU fuel reaches its maximum on the verge of the range of the ^{236}U content (see Fig. 4). This error does not exceed 0.024% for any ^{236}U content in the range of 0.1-1.0% for ERU fuel with an effective enrichment of 4.0% ^{235}U.

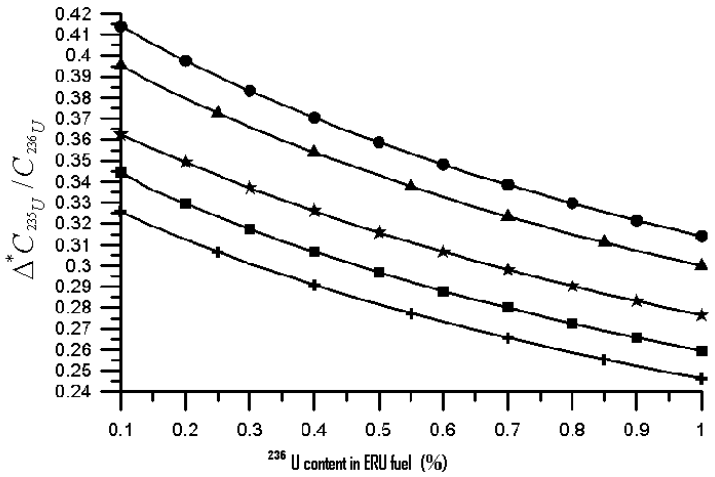

FIG. 2. $\Delta^* C_{235_U} / C_{236_U}$ *value versus the* ^{236}U *content in ERU fuel. WWER fuel assembly with equivalent* ^{235}U *enrichments of:* ✚ *3.3 %;* ■ *3.6 %;* ✱ *4.0 %;* ▲ *4.4 %;* ● *4.6 %.*

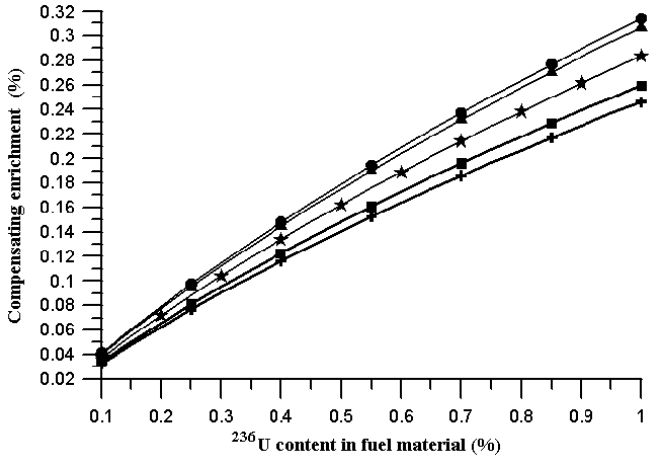

FIG. 3. Compensating enrichment (in % ^{235}U*) versus* ^{236}U *content in WWER fuel rods with equivalent* ^{235}U *enrichments of:* ✚ *3.3 %;* □ ■ *3.6 %;* ✱ *4.0 %;* ▲ *4.4 %;* ● *4.6 %.*

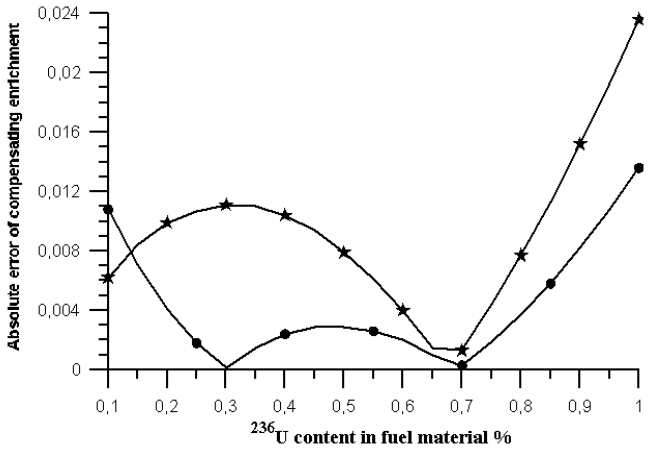

FIG. 4. Absolute error of compensating enrichment versus ^{236}U *content in WWER-1000 ERU fuel rods with equivalent enrichment of 4.0 %* ^{235}U*:* ✱ *precise calculations;* ● *linear approximation.*

The content of ^{234}U and ^{236}U were compensated in ERU fuel with an equivalent enrichment between 3.3 and 4.6% ^{235}U. The relative ^{236}U mass fraction in the fuel was within the range of 0.1~1.0%. The considered change of the ^{234}U and ^{236}U content in the fuel was in the range of 0.02~0.065%.

3. Analysis of operational experience with ERU fuel assemblies in the WWER-440 reactor unit Kola-2

In 2002, as the 25th reload of the Kola-2 NPP unit, the first pilot fuel batch comprising 54 fixed fuel assemblies (FFA) with an average enrichment of 3.82% ^{235}U, 12 ERU fuel assemblies with an equivalent enrichment of 3.82% and 12 CPS fuel assemblies was put into the reactor core. The 25th fuel reload was the first transient fuel reload of the 4-year fuel cycle. It started on 10 May 2002 and ended on 16 May 2003 (234.2 effective days). During the 25th, the 26th and the 27th fuel reloads profiled FFAs with an enrichment of 3.82% ^{235}U were used, including ERU fuel assemblies.

For each of the above fuel reloads, the results of the operational measurements were compared with the results of calculations for 200 points. The results of comparisons showed that operational measurement data in general corresponded to neutron and physical calculation data. This confirms the correctness of calculation information about the burnup fraction per core.

The analysis of the fuel reloads' operational data, particularly detailed results of the fuel failure detection system control for the 25th, the 26th and the 27th reloads proved that there were no violations of limits and conditions regarding the safe operation of Kola-2.

4. Analysis of operational experience with ERU fuel assemblies in the WWER-1000 reactor unit Kalinin-2

As part of the 15th reload of the Kalinin-2 NPP unit, a pilot batch of 12 TVSA fuel assemblies containing ERU (made of RepU in form of uranyl nitrate) was put into the reactor core. The ERU fuel assemblies were placed symmetrical to the ENU fuel assemblies to test the identity of the physical characteristics of ERU and ENU fuel assemblies. During the 16th fuel cycle, the operation continued with 12 TVSA ERU fuel assemblies. During the reactor's 17th reload, 18 TVSA ERU fuel assemblies (made of RepU in form of uranium dioxide powder produced by the ADU technology) were installed in the core.

In May 2004, operation of the 17th fuel reload started. This reload comprised 54 TVSA ENU fuel assemblies of the third year of operation, 49 TVSA ENU fuel assemblies of the second year of operation and 48 'fresh' TVSA fuel assemblies, among them 18 TVSA ERU fuel assemblies. Figure 5 shows the dynamics of TVSA ERU fuel ('UR TVSA') loading at Kalinin-2.

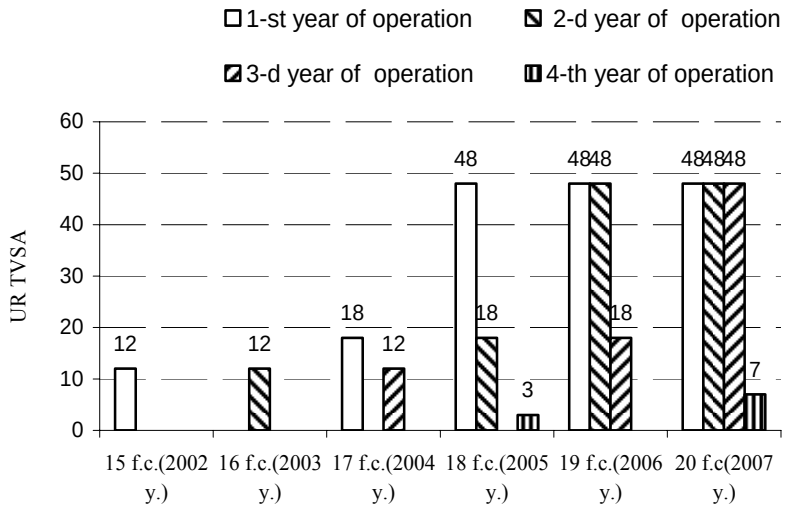

FIG. 5. The dynamics of TVSA ERU fuel (UR TVSA) assemblies loaded in Kalinin-2.

By the end of the 17th fuel cycle, the following operational experience had been achieved with TVSA ERU fuel:

- Maximum burnup per fuel assembly (average): 45.6 MW•d/kg U.
- Maximum burnup per fuel rod (average): 47.8 MW•d/kg U.
- Activity of iodine in coolant: 7.2×10^{-6} Ci/kg (average) and 1.1×10^{-5} Ci/kg (maximum) which is less than the operational limit.

By the end of the 18th fuel cycle, the maximum burnup the TVSA ERU fuel assemblies will be 48 MW•d/kg U (estimated forecast). The results of the fuel failure detection system control showed that during the 15th through the 18th fuel cycles there were no ERU fuel rod failures. Currently the operation of TVSA ERU fuel assemblies in Kalinin-2 continues.

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The ERU fuel manufacturing at AREVA NP

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Abstract. Within the Fuel Manufacturing Business Unit (FMBU) of the AREVA NP Fuel Sector, the FBFC Romans fuel plant has manufactured enriched reprocess uranium (ERU) fuel assemblies. The plant has acquired a long standing experience in this manufacturing area. Since the first ERU manufacturing campaign took place at Romans in 1987 on behalf of Electricite de France (EDF), more than 400 tonnes ERU fuel assemblies were produced. Romans is currently licensed to manufacture 150 tonnes ERU fuel per year on the basis of a specification included into the general technical instructions of the plant with especially a maximal ^{232}U content of 15 ppb. The following radiological issues has been considered in ERU fuel fabrication: i) the external exposure is mainly due to the ^{232}U decay products, ii) the emission from ERU is 10% higher than from enriched natural uranium (ENU), iii) the contribution of neutrons to the external exposure is very low, and iv) the dose rate level increases with time. The main management principles regarding the internal and external exposure of the manufacturing personnel through all the manufacturing steps (UF_6 re-conversion, pelletizing, rod and fuel assembly manufacturing) are the following ones: a) to reduce the lead time of the ERU material in the whole facility, b) to control the material storage areas regularly, c) to identify and inspect the places where the material can be accumulated, d) to control the full UF_6 cylinders, e) to control the empty UF_6 cylinders by knowing that the ^{232}U decay products remain in the cylinder during the UF_6 evaporation, f) to load the ERU fuel assemblies in the containers immediately after their manufacturing, and g) store the loaded assembly containers at the rear of the storage room with a specific labelling in a restricted access area. Moreover, the Romans fuel plant is being renewed to be able by the end of 2008 to manufacture both ENU and ERU fuel. After that renewal all the equipments will comply with the most stringent standards regarding safety and environmental protection and will achieve the highest quality and productivity level.

1. Introduction

The Fuel Manufacturing Business Unit (FMBU) within the AREVA NP Fuel Sector represents the largest fuel manufacturing capacity worldwide. Four facilities of the FMBU are licensed to manufacture enriched reprocess uranium (ERU) fuel assemblies (FA) with specific local requirements: Richland (USA), Lynchburg (USA), Romans (France), and Lingen (Germany).

Although the plant at Lingen has already started to produce ERU fuel rods and fuel assemblies in 1983, the plant at Romans has acquired also a very long-standing experience and it will remain the reference facility for ERU fuel assemblies in future.

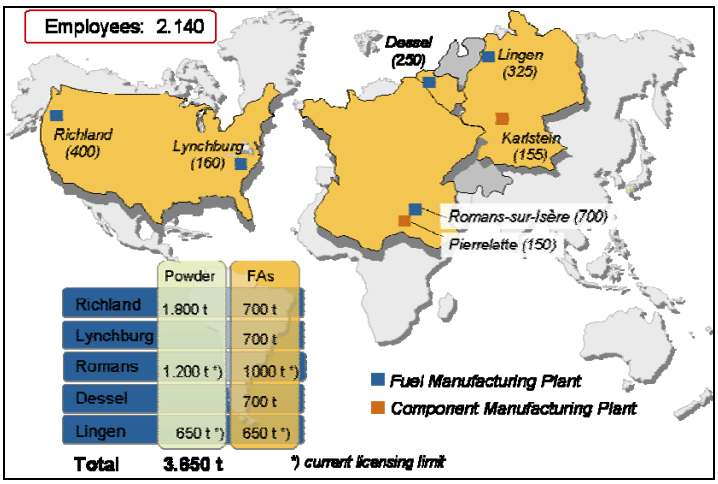

FIG. 1. AREVA NP fuel manufacturing business unit plants.

2. ERU manufacturing experience at Romans

Over the years, the plant at Romans has acquired a significant experience in manufacturing ENU and ERU fuel assemblies.

The manufacturing of the fuel assemblies is performed through several process steps. The plant receives in 30B containers the enriched natural or reprocessed UF_6 which is first converted into UO_2. The UO_2 powder is produced by dry route re-conversion that leads to a high quality powder with stable characteristics thanks to good process stability and permanent control of the working parameters.

After blending, the powder is pre-compacted, granulated and pressed into pellets on a rotary press. Then the green pellets are sintered in a furnace under dry hydrogen atmosphere. The sintered pellets are wet grinded and inspected before temporary storage. Finally, the pellets are loaded into the rods and the fuel rods are assembled into fuel assemblies.

The manufacturing process for the ERU fuel is the same as the one implemented for the ENU fuel. However, the ERU fuel is fabricated on lines with special radioprotection features, as explained below. Once manufactured, ERU fuel assemblies are packed into transport containers and shipped to the utility.

The safety demonstration to obtain the appropriate authorization to manufacture ERU fuel assemblies in Romans was long and heavy, and was developed in several steps.

The first ERU fuel manufacturing campaign at Romans was performed for EDF in 1987. Between 1987 and 2000, the French Safety Regulation Authority (DGSNR) granted a specific license for every manufacturing campaign. In 1994, considering the fabrication feedback, it was decided to upgrade one of the two fuel lines of the plant. Thus, the upgraded line became the only line licensed to manufacture ERU fuel assemblies at Romans.

On 7 August 2000, the DGSNR granted to Romans a generic license to manufacture 150 tonnes ERU fuel per year on the basis of a specification included into the safety general technical instructions of the plant. The technical instructions are given by the DGSNR and can be modified – even temporarily - only with the agreement of the DGSNR General Manager.

In April 2005, a new rod and assembly line started on which two ERU campaigns for EDF were manufactured so far.

By the end of 2006, around 406 tonnes ERU FAs were produced.

TABLE 1. FBFC ROMANS ERU FUEL ASSEMBLY CAMPAINGS

Batch #	Enrichment	Type	FA Quantity	kgU	Delivery Date	REMARK
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	3,55%	17 LRT	4	1 838	Aug-87	232U content between 3 and 8 ppb
URE/01	3,70%	17 AG2	26	11 947	Dec-93	
[illegible]	[illegible]	[illegible]	34	[illegible]	[illegible]	232U content between 6 and 11 ppb
URE/02	3,70%	17 AG2	42	19 299	Mar-95	
[illegible]	[illegible]	[illegible]	32	[illegible]	[illegible]	
URE/03	3,70%	17 A2 G	44	20 218	Jan-96	
URE/04	3,70%	17 A2 G	44	20 218	Feb-96	
[illegible]	[illegible]	[illegible]	32	[illegible]	[illegible]	
URE/05	3,70%	17 A2 G	40	18 380	Nov-96	
URE/06	3,70%	17 A2 G	36	16 542	Mar-97	
[illegible]	[illegible]	[illegible]	32	[illegible]	[illegible]	
URE/07	3,70%	17 A2 G	36	16 542	Mar-98	
URE/08	3,70%	17 A2 G	44	20 218	Jun-98	
[illegible]	[illegible]	[illegible]	32	[illegible]	[illegible]	
URE/09	3,70%	17 A2 G	44	20 218	Feb-99	
URE/10	3,95%	17 A2 G	40	18 380	May-99	
[illegible]	[illegible]	[illegible]	36	[illegible]	[illegible]	
URE/11	3,95%	17 A3 G	36	16 542	Jan-00	
[illegible]	[illegible]	[illegible]	30	[illegible]	[illegible]	
URE/12	3,95%	17 A3 G	40	18 380	May-01	
URE/13	3,95%	17 A3 G	36	16 542	Feb-02	
[illegible]	[illegible]	[illegible]	28	[illegible]	[illegible]	
URE/14	3,95%	17 A3 G	40	18 380	Jul-03	
[illegible]	[illegible]	[illegible]	28	[illegible]	[illegible]	
URE/15	3,95%	17 A3 G	40	18 380	Nov-03	
URE/16	3,95%	17 A3 G	40	18 380	Mar-05	
URE/17	3,95%	17 A3 G	40	18 380	Apr-05	
URE/18	3,95%	17 A3 G	40	18 380	Jun-06	232U content = 15 ppb
TOTAL			1006	406519		

3. License and requirements

The Romans plant is currently licensed to manufacture a maximal quantity of 150 tonnes ERU fuel per year with the following maximal isotopic composition:

- $^{232}U < 15$ ppb;
- $^{234}U < 0.15$ %;
- $^{235}U < 5$ %.

and with the fission products referring to the ASTM C 996-90 standard.

Considering these limits, the current radioprotection objectives of the FBFC Romans plant are the following ones:

- External exposure only < 15 mSv/a;
- External + internal exposure < 5 mSv/a external + 10 mSv/a internal.

Furthermore, the Romans facility is being renewed. At the end of the renewal, the radioprotection performance will be improved and the objectives will be the following ones:

- External exposure only < 5 mSv/a;
- External + internal exposure < 2.5 mSv/a external + 2.5 mSv/a internal.

4. Management of the fabrication flow (re-conversion, pelletizing, rod and fuel assembly manufacturing)

4.1. Main manufacturing organization principles regarding the internal and external exposure

Considering that:

- the external exposure is mainly due to the ^{232}U decay products;
- the β emission from ERU is 10% higher than from ENU;
- the contribution of neutrons to the external exposure is very low (like ENU); and
- the γ dose rate level increases with time.

the main manufacturing organization principles regarding the internal and external exposure are driven by the reduction of the lead time of the ERU in the whole facility, the regular control of the material storage areas, the identification and the inspection of the places where the material can be accumulated, and the control of the full UF_6 cylinders and the empty UF_6 cylinders by knowing that the ^{232}U decay products remain in the cylinder during the UF_6 vaporization.

4.2. Management of the UF_6 containers

The same containers as for ENU are used for the transportation of ERU (in form of UF_6). The plant at Romans is authorized to store a maximum UF_6 quantity of 285 t U (ENU plus ERU) on site.

The dose rate level measured on contact with the full UF_6 cylinder shows the self-absorption of the UF_6 within the containers while the dose rate level on contact with the empty containers is higher than with the full cylinders. As a consequence, the main radioprotection measures aim to limit the stay of the cylinders and the operators on the storage. In that way, a dedicated area has been created for ERU with a delay of youth longer than 3 months and for the empty containers with a dose rate higher than 2 mSv/h.

In order to have a close following up, the radiation rate is measured weekly around the area. Furthermore, a radiation measurement is performed on every incoming cylinder with search of the maximal value. In addition, every cylinder with search of the maximal value is inspected weekly and an operational dosimeter is dedicated to the employees operating in the area.

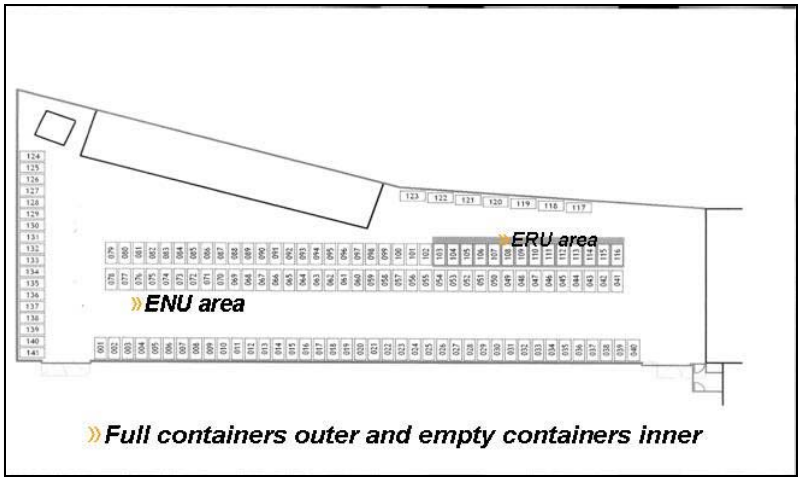

FIG. 2. FBFC Romans UF_6 cylinder storage area.

4.3. ENU and ERU flow separation principle for the UF_6 re-conversion

For the re-conversion of ENU and ERU from UF_6 to UO_2, all the kilns can be used with the following principles:

- There is no further mixing between ERU and ENU even if the ^{235}U content is the same one. Thus, a very deep cleaning is needed before starting a new campaign.
- At the end of the campaign the kiln must rotate without producing in order to empty the kiln to the maximum possible extent before the next load.
- The first produced batch of the next campaign is isolated and analyzed before a possible use.

If a blending of the UO_2 powder is needed, only two blenders can be used for the ERU. They require an in-depth cleaning at the end of each ERU campaign.

4.4. ENU and ERU flow separation principle for the pelletizing

Prior to the on-going Romans upgrading, only one line could be used for the pelletizing operations (i.e. from blending of the powder to grinding of the pellets). That line had specific protections for ERU, such as:

- additional confinements around the equipments (blending, granulation, pressing, sintering, grinding) with glove boxes;
- airlock access for the containers;
- lids on the pellet box supports; and
- enclosure on the entering pellet boxes to be sintered.

In addition, some general management rules are implemented, such as:

- a specific labelling of the campaign,
- an in-depth cleaning of the equipments before, during and after the campaign of the equipments, the structures and the ground,
- a specific surveillance by the team supervisor, and
- a preventive replacement of the gloves.

The stand with the highest radiation level is the pellet inspection bench; therefore, specific radioprotection measures are applied. They consist of measuring at contact and at a distance of 50 cm the radiation level on 3 pellet trays and of performing an annual campaign of finger ring dosimeter during 1 quarter for 10 operators.

4.5. ENU and ERU flow separation principle for the rod and assembly manufacturing

Currently only one line (which started in 2005) can be used to produce ERU fuel rods and ERU fuel assemblies (i.e. from the loading of the pellets until the inspection of the fuel assemblies). In this workshop, a specific marking for the working stations and the storage areas is implemented.

The two operations with the highest radiation level are the pellet loading into rods and the rod loading into an assembly. Thus, in order to minimize the radiation level, a limitation of the rod Work In Progress (WIP) is recommended depending on the operator position (1, 25, 50 or 100) with sensors stopping the process along the line when the maximal quantity is reached.

FIG. 3. FBFC Romans fuel rod line.

The specific measures implemented are the following ones:

- a special confinement and only one pellet cabinet at the pellet loading bench;
- transfer of the scrapped rods per piece at the rod final inspection flat table in order to avoid the use of the trays;
- avoid as much as possible the intermediate rod storage in tray and store the tray as far as possible away from the operators;
- a steel shielding at the pulling machine due to the operator's long length of stay and only one loaded bench used at once for the assembly mounting;
- a steel cabin (6 mm thick) with lead glass (11 mm thick) due to the operator's long length of stay at the fuel assembly visual inspection pit;
- loading of the assemblies into the containers immediately after their manufacturing; and
- store the loaded assembly containers at the rear of the storage room with specific labelling in a restricted area.

5. Transportation of ERU powder and ERU fuel assemblies

5.1. Powder

The containers used for ENU powder (TNUO2 and TNF-XI) can be used also for ERU powder and a specific sheet related to the ERU material is added into the transportation license. For instance, AREVA NP uses TNF-XI to deliver ERU powder to Japan. There is no ERU dedicated powder transport container fleet.

5.2. Fuel assemblies

The AREVA NP FCC containers are licensed to transport ENU and ERU fuel assemblies. Indeed, the internal structure of the FCC leads to a dose rate reduction in comparison to the former RCC containers (from 10 to 20 µSv/h).

FIG. 4. AREVA NP FCC fuel assembly container.

6. Management of the ERU scraps and other ERU process residues

6.1. The hydrofluoric acid from ERU

Hydrofluoric (HF) acid is obtained during the dry re-conversion process which transforms UF_6 into UO_2 powder. The HF from ERU is treated by the same process as the one from ENU.

Some specific measurements are regularly performed on several samples taken from the HF acid generated during the re-conversion process. Most of the results are below the detection limit. The exceptions are without any consequence for the management of the HF: The uranium content (around 0.12 µgU/L) is largely below the customer specification (3 ppm), and the ^{99}Tc content of 0.22 Bq/L is below the activity of the U.

6.2. ERU scraps recovering from powder manufacturing and pelletizing

A specific labelling of the scraps is implemented. The treatment of the ERU scraps through the recycling shop in Romans is the same wet process as for the ENU scraps. The final residues are sent to AREVA NC Pierrelatte to be compacted, put into concrete and sent to ANDRA for final disposal.

FIG. 5. FBFC Romans HF station.

7. Evolution of the Romans plant over the next years

The Romans plant is being renewed to be able to manufacture ENU as well as ERU fuel by the end of 2008. It will comply with the most stringent standards regarding safety and environmental protection and will achieve the highest quality and productivity level.

The improved standards applied for the new lines for ERU (and for ENU as well) are:

- confinements for all the equipments and U transport means;
- airlock system for all powder or pellet transfers; and
- automated transport and transfer equipments.

At the end of the project, the plant at Romans will be licensed to produce ERU fuel on all the equipments with the current assay (especially $^{232}U < 15$ ppb) and at a maximum throughput of 150 tonnes ERU per year.

Nevertheless, considering the evolution of the isotopic content of the ERU, a study is going on to identify the additional improvements needed to accept the future assay (especially $^{232}U < 37$ ppb).

PROCESSING OF RepU

(Session 4)

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Reprocessed uranium experience and UK options for NDA and Springfields Fuels Limited

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Abstract. The Nuclear Decommissioning Authority (NDA) is the owner of over 20 000 t U of uranium arising from the reprocessing of Magnox fuel, known in the United Kingdom (UK) as Magnox Depleted Uranium (MD U). This material is stored in the form of uranium trioxide (UO_3) at the NDA's Capenhurst site. The NDA Strategy, published in March 2006, indicated that solutions to deal with MD U would be sought and that NDA would engage with the UK Government and UK Stakeholders to consider the most appropriate management strategies for uranic material. Springfields Fuels Limited (SFL), currently operated by Westinghouse, has recycled over 15 000 t U of MD U reprocessed uranium though its manufacturing facilities in production campaigns between the 1970s and the early 1990s. UO_3 was converted to uranium tetrafluoride (UF_4) in reduction and hydrofluorination kilns before being converted to uranium hexafluoride in the now decommissioned UF_6 plants. Following enrichment, the UF_6 was converted to uranium dioxide (UO_2) via the integrated dry route kiln process and manufactured into fuel assemblies for the UK's advanced gas-cooled reactors (AGR), operated by British Energy (BE). SFL has also demonstrated conversion of limited quantities of oxide reprocessed product. The paper provides details of reprocessed uranium stocks in the UK, NDA's stakeholder engagement and reviews SFL's experience from recycling uranium at Springfields which can help contribute to finding optimal solutions for UK reprocessed uranium issues.

1. Introduction

The NDA is a non-departmental public body which was set up in April 2005 to take strategic responsibility for the UK's nuclear legacy. As part of its strategic commitment, the NDA is carrying out an evaluation of the potential liability or asset of the UK's stocks of civil separated uranium and plutonium which includes reprocessed uranium (RepU). In total, these stocks comprise approximately 60 000 tHM of which the NDA has ownership of over 80%. The balance of the stocks is held by the Ministry of Defence (MOD) and British Energy. Currently all of the NDA material is held in purpose-built stores on NDA sites and financially are classed as assets of zero value. The amount of this material which is RepU in the form of UO_3 is expected to be in excess of 30 000 t U.

The NDA commissioned a Study by Environmental Resources Management Limited (supported by Integrated Decision Management) [1], to provide an economic analysis of potential future disposition options for the UK's stock of nuclear materials. It lays out different potential futures and determines their financial, socio-economic and environmental impacts. The Study analyses a range of options from declaring all the materials to be wastes through to a case with maximum re-usage as fuel. It makes no presumptions about where any recycled fuel would be used, but enables a variety of reactor assumptions to be examined. It does not set out a preferred option or make any recommendations on

options to the NDA or to the UK Government. This paper will focus only on RepU disposition and the various options that could be available.

2. Uranium stocks

In the UK, stocks of RepU come from two different sources: the reprocessing of metal fuel from the Magnox reactors and the reprocessing of oxide fuel from AGRs and light water reactors (LWR).

The most significant quantities of RepU come from the Magnox reactors, the majority of which REPU is owned by the NDA. As of today there is approx. 24 000 t U of MD U which has been processed and being stored. Following the planned closure of the remaining Magnox reactors by 2010 it is currently estimated that there will be in excess of 30 000 t U of MD U available by around 2012. The MD U has been recovered in the form of UO_3 and has a ^{235}U content of typically 0.4%. Due to the low burnup of the natural enriched uranium metal fuel, the ^{232}U and ^{236}U isotopes are low.

There are also various quantities of Thorp product RepU (TPU) from the reprocessing of oxide fuel from AGRs and LWRs. This material is owned by the NDA, BE and several overseas reprocessing customers. Currently there is over 2000 t U of AGR derived TPU with the potential for up to 5000 t U in total, depending on future reprocessing schedules. In addition, there are stocks of overseas material which are contracted to be repatriated to their owners. The uranium isotopics for the Thorp material are quite variable with the ^{235}U content typically in the range 0.8 to 1.0%.

3. Springfields experience

Approx. 15 000 t U of MD U has already been recycled at Springfields and utilised in AGR fuel. A total of 1600 t U of fuel was manufactured and successfully irradiated in the UK AGRs. Recycling of MD U in the AGRs ended in the 1990s for economic reasons. The last campaign of 1218 t U of MD U was processed in 1991. However, the recent increases in uranium oxide concentrate (UOC) prices have improved the economics for the recycling of MD U material.

The relatively low radioactivity levels of the MD U material simplified the arrangements required for use of this material for the manufacture of the AGR fuel. The MD U was brought to the Springfields plant where a number of the existing facilities were utilised to process the material. Currently the MD U is stored in steel drums. However, due to the absorption of water from the atmosphere it forms a solid crust of hydrated UO_3 which needs to be broken up prior to it being emptied from the storage drum or further processed. In one facility, the UO_3 powder was initially converted to uranium tetrafluoride (UF_4) in reduction and hydrofluorination kilns before being transferred to the UF_6 facility for conversion to uranium hexafluoride. The depleted UF_6 was then transported to the Capenhurst plant for enriching to the required levels of between 2.5 and 3.5% ^{235}U for AGR fuel. The enriched UF_6 was then returned to Springfields where it was converted to UO_2 powder via the integrated dry route kiln process and ultimately pelleted and manufactured into AGR fuel assemblies. Few special precautions were put in place to handle the MD U during processing, although a UF_4 to UF_6 conversion facility was scheduled for decommissioning following completion of its last MD U campaign. The effect of the ^{236}U on enrichment penalty was so small that no compensation was necessary on the MD U campaigns which simplified the manufacturing process and eliminated the need for any segregation of these campaigns.

While experience with RepU from oxide fuel has been limited, there has been a successful demonstration campaign in which a few tonnes of granules were produced from feed UF_6. In this campaign, material was fast tracked through the facilities to keep dose levels low and compliant with the safety case. Some of the facilities used were subsequently decontaminated to the extent necessary for continued operations with non-irradiated material.

4. Strategic options

The NDA-commissioned Study evaluated multiple scenarios for the disposition of its stocks of nuclear materials. It identified three bounding scenarios which encompass all the other potential options. These three were:

- Scenario 1: Declare as waste;
- Scenario 2: Store pending a decision to use or declare as waste; and
- Scenario 3: Use by recycling to the optimum extent possible.

A decision on the way forward will be very dependent on an assessment of the future price projections for uranium and the future demand for uranium required to supply worldwide nuclear generation capacity. The stocks held by the NDA would be considered as secondary sources of uranium and such stocks are becoming increasingly commercially attractive.

4.1. Declare as waste

In this scenario, all of the NDA's RepU is designated as waste and will be disposed of in a deep geological disposal site, the UK Radioactive Waste Repository, as soon as practical after opening (depending on the priority of material for disposal). There is a small uncertainty as to whether the case can be made to dispose of the RepU as UO_3. The alternative would be to convert the UO_3 to less soluble U_3O_8 or UO_2. Existing technology and facilities could be utilised to do this, but dependent on timing, the building of new facilities cannot be ruled out. As a minimum, a new Intermediate Level Waste (ILW) storage repository will need to be built to accommodate the disposed material and would be expected to be available around 2040. Disposal of all waste is assumed to be complete by 2125 and the repository closed.

The principle cost uncertainties associated with this scenario are in respect of the acceptable form of the waste and the availability of the storage repository.

4.2. Store pending decision on recycle or disposal

The key presumption is that the available RepU has value and a reasonable prospect of being recycled. The RepU will be regarded as a strategic resource and will be stored in its current form. It is recognised that there may be some material which will not be possible to recycle and this will be designated as waste. Ultimately, if any of the stored RepU is not utilised, then it will be conditioned as necessary and designated and disposed of as waste per Scenario 1 above. Storage will not be an open ended commitment and the NDA Study assumes disposal would have to take place within the Committee on Radioactive Waste Management's 300 year timeframe. For the purpose of the Study, it is further assumed that another new additional ILW repository would be required on a timescale of 260 years from now to support any such disposal as the planned UK repository is likely to have closed before then.

The costs of this scenario have some of the same uncertainties and sensitivities as for Scenario 1 above.

4.3. Use

As with Scenario 2, material with a reasonable prospect of being recycled will be differentiated from other material which will not be possible to recycle. The latter material will be designated as waste and disposed of per Scenario 1. For the purpose of the NDA Study, it would be proposed to recycle the RepU as fuel through Pressurized Water Reactors (PWR), although it is acknowledged that other reactor types could be considered. It is estimated that the RepU stocks available would be sufficient to fuel between 0.4 and 1.9 PWRs of the 1000 MW(e) size over their 60 year lifetime.

To develop and implement this recycle route could require significant investment in a number of facilities. Within the UK, the NDA's Springfields site has the skills and experience to potentially accommodate the expected capacity needs:

- A new RepU Conversion Facility: This would be capable of converting UO_3 (both MD U and TPU) to UF_6 prior to re-enrichment. In the late 1990s such a facility was designed and partially constructed at Springfields to handle TPU but was not commissioned due to a weakened business case given the prevailing market conditions. This facility was designed to accept either UO_3 or U_3O_8 with enrichments up to the order of 1.1% ^{235}U and with radiological specifications of up to 2ppb average ^{232}U, 10 year aged equivalent. Feed material was to be converted to UF_4 using SFL's well-established kiln technology. Conversion of the UF_4 to UF_6 would then take place using a tube reactor process. The facility was subsequently decommissioned without becoming active. A new facility would be sized to handle the anticipated 30 000 t U or more of feed material expected to be processed over the coming decades.

- Re-enrichment: This would be an externally sourced service currently available from several organisations.

- An upgraded/new fuel fabrication facility: The assumption modelled in Ref. [1] is that the recycled fuel will be used for PWR fuel manufacture. The Springfields site has a facility called the Oxide Fuel Complex (OFC) which became operational in the mid-1990s. It is currently used for AGR fuel manufacture and has in the past been used for PWR fuel manufacture. The facility takes enriched UF_6 through to finished fuel assemblies. For the recycled material, the existing facility will either be suitably modified or a new facility will need to be built. In principle, the existing OFC facility is capable of being modified to accept additional shielding as this was envisioned as part of its original design specification. The OFC facility already incorporates a high degree of remote operation and automatic handling techniques and average doses in the facility are typically below 1mSv. However, there may be benefits from having a new dedicated facility with integral shielding, which will avoid any potential cross contamination and will allow for better management of residues, etc.

Under this Scenario it is assumed that all of the material, after recycling, will ultimately go for disposal within a timeframe of 300 years.

The costs associated with this Scenario will be offset by the worth of the RepU being recycled. The value of the RepU can be assessed by the price which can be obtained for the fuel which is related to the price of fuel made from non-irradiated uranium. The fuel price increases with uranium price and is also dependent on the US dollar exchange rate so that the relative cost of this scenario reduces as the uranium price rises and the dollar weakens. Consequently there is considerable uncertainty in the determination of the net discounted costs which have been assessed to range from a negative cost (i.e. overall benefit) to a positive cost similar to that of the waste disposal Scenario 1.

5. Summary

The NDA is evaluating several disposition options for discharging its strategic responsibility for its stocks of nuclear material. This includes significant quantities of RepU material in the form of UO_3 most of it originating from the reprocessing of Magnox fuel, but there is also a smaller quantity of material from the reprocessing of oxide fuel. In the past there has been considerable experience gained at Springfields recycling the relatively low activity Magnox-derived RepU into finished fuel assemblies. The NDA Study of its disposition options identified a number of different scenarios but focused on three bounding scenarios (waste, store, use), which encompassed the other scenarios. The key conclusions from the Study were broadly that:

- waste is low risk and, if the uranium price is low, it is either the lowest undiscounted cost option or close to it;
- store keeps options open and delays costs for significant periods (significantly reducing the present value of costs when discounted), but undiscounted costs are significantly higher in the long term;
- use may release significant value from the materials (particularly if the uranium price is high), but is subject to significant downside risks.

The NDA will want to take these findings into account in its discussion with Government on the options for the future.

REFERENCE

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Reprocessed uranium handling at Siberian Group of Chemical Enterprises

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Abstract. This paper describes the experience of treating reprocessed uranium (RepU) at the Siberian Group of Chemical Enterprises (SGChE). SGChE is a nuclear fuel cycle production center. It has been working with nuclear technologies for more than 10 years. The SGChE's production is shipped both into the Russian Federation's market and the international market. SGChE has been active on the international enrichment services market since 1993. The experience of processing RepU at SGChE includes the following activities: the purification at the radiochemical plant of spent slightly irradiated fuel from two commercial reactors operated by SGChE operated reactors and also RepU from power reactors, the conversion of uranium with up to 1% U^{235} into hexafluoride at the conversion plant, and the enrichment of uranium hexafluoride with up to 5% U^{235} using the gas centrifuge equipment of the enrichment plant. In 1992, the SGChE started the commercial-scale conversion and enrichment of RepU derived from spent power reactor fuel imported from France. Over seven years, SGChE processed a total of about 1700 tonnes RepU. The SGChE has capacities to process up to 1500 tonnes of RepU per year with further rendering enrichment services totalling about 1 million SWU.

1. Introduction

the Russian Federation pioneered the induction of reprocessed uranium (RepU) into the nuclear fuel cycle. The closure of the nuclear fuel cycle was applied for the first time for RepU extracted from spent fuel of commercial graphite-uranium reactors, the so-called 'RF' (reactor fuel) specification feedstock.

During the next stage, the production facility RT-1 was commissioned in 1977 at the Production Association 'Mayak' (PA 'Mayak') where RepU uranium extracted from the spent fuel of Water-Cooled and Water-Moderated Reactors 440 (WWER-440) was enriched by blending in nitric acid solution with RepU extracted from spent fuel of research reactors and marine application plants. The obtained uranyl nitrate of up to 2.6% ^{235}U was shipped to branch facilities for the manufacturing fuel pellets, fuel cells and assemblies for light water-cooled, graphite-moderated reactors (RBMK) (i.e. multi-channel high power reactors).

And finally, over the 1992 to 1998 time period, the SGChE performed the commercial-scale conversion and direct enrichment of RepU derived from spent power reactor fuel imported from France. Over seven years, SGChE processed a total of about 1700 tonnes RepU. In 2004, SGChE resumed the recycling of imported RepU.

2. Reprocessed uranium enrichment schemes

In the Russian Federation (USSR), there are different schemes to re-enrich RepU: At PA 'Mayak' and at OAO 'Mashinostroitelny Zavod' (Machinery Works) the enrichment is performed by blending RepU with medium (MEU) or highly enriched uranium (HEU), whereas SGChE employs the conventional enrichment technique, i.e. a gas centrifuge cascade. Each method has both advantages and disadvantages.

Conventional enrichment technique

Uranium isotope separation using gas centrifuges falls into the group of molecular separation methods. The physical foundation of this method is as follows: In the centrifugal field molecules of different masses are affected by centrifugal forces of different magnitudes. The isotope separation factor depends on the molecular mass differences. Light-mass molecules are enriched to form the product in the cascade, and, consequently, heavy-mass molecules are enriched to go to the waste. As about 99% of the RepU are made up by the heavy isotope ^{238}U, all other uranium isotopes – ^{232}U, ^{234}U, ^{235}U, and ^{236}U – concentrate in the product.

Thus, the main disadvantage of re-enriching RepU by using a separation cascade is the accumulation of minor isotopes in the product. The second disadvantage is the production of of tails.

Table 1 shows the isotopic composition of RepU feed and of low enriched reprocessed uranium (ERU) obtained in the separation cascade as well as the feedstock consumption and separative work input needed per 1 kg of product.

TABLE 1. ISOTOPIC COMPOSITION OF REPU FEEDSTOCK, TAILS AND ENRICHED REPROCESSED URANIUM AND CONSUMPTION OF REPU FEEDSTOCK AND SWU

Uranium Isotopes/Units	Reprocessed Uranium Feedstock	Tails	Enriched Reprocessed Uranium (ERU)
^{232}U (%)	2.0×10^{-7}	1.0×10^{-8}	1.27×10^{-6}
^{234}U (%)	0.024	0.0036	0.137
^{235}U (%)	0.99	0.3	4.8
^{236}U (%)	0.45	0.244	1.586
Uranium (kg)	6.522	5.522	1.0
Separative Work (SWU)	–	–	5.129

Table 1 shows that the concentration of ^{232}U in the end product has increased by a factor of 6.4, the concentration of ^{234}U by a factor of 5.7, and that of ^{236}U by a factor of 3.5. The end product constitutes 15% of the feedstock mass, the balance of 85% flows to the waste (tails). Pursuant to the following sections of this paper, handling of the end product obtained from RepU is most adversely affected by a high content of ^{232}U which features the highest concentration factor when enriched.

The concentration of minor isotopes in the end product obtained from RepU can be reduced by diluting it with the product of the same enrichment produced from from natural uranium (enriched natural uranium, ENU). Table 2 illustrates this dilution.

TABLE 2. ISOTOPIC COMPOSITION OF REPU FEEDSTOCK, ERU, ENU AND BLEND AND CONSUMPTION OF RepU FEEDSTOCK AND SWU

Uranium Isotopes/Units	Reprocessed Uranium Feedstock	Enriched Reprocessed Uranium (ERU)	Enriched Natural Uranium (ENU)[1)]	Blend of ERU and ENU
^{232}U (%)	2.0×10^{-7}	1.27×10^{-6}	1.0×10^{-8}	1.99×10^{-7}
^{234}U (%)	0.024	0.137	0.049	0.0622
^{235}U (%	0.99	4.8	4.8	4.8
^{236}U (%)	0.45	1.586	0.009	0.246
Uranium (kg)	–	0.15	0.85	1.0
Separative Work (SWU)	–	0.769	5.788	6.557

1) Natural uranium product quality represented in the Table complies with ASTM C 787.

The Table shows that when ERU is diluted with ENU in the ratio of 1 to 5.7, the ^{232}U content in the blend is the same as in the RepU feedstock, and the ^{236}U content is even lower than in the feedstock. Therewith, it does not result in the loss of separative work expended to obtain these products, contrary to the RepU processing schemes in which the RepU feedstock is blended it with medium or highly enriched uranium. The drawback of this option is the necessity of involving pure feedstock, thereby obtaining an increasing amount of product (blend) with a quality specific for RepU.

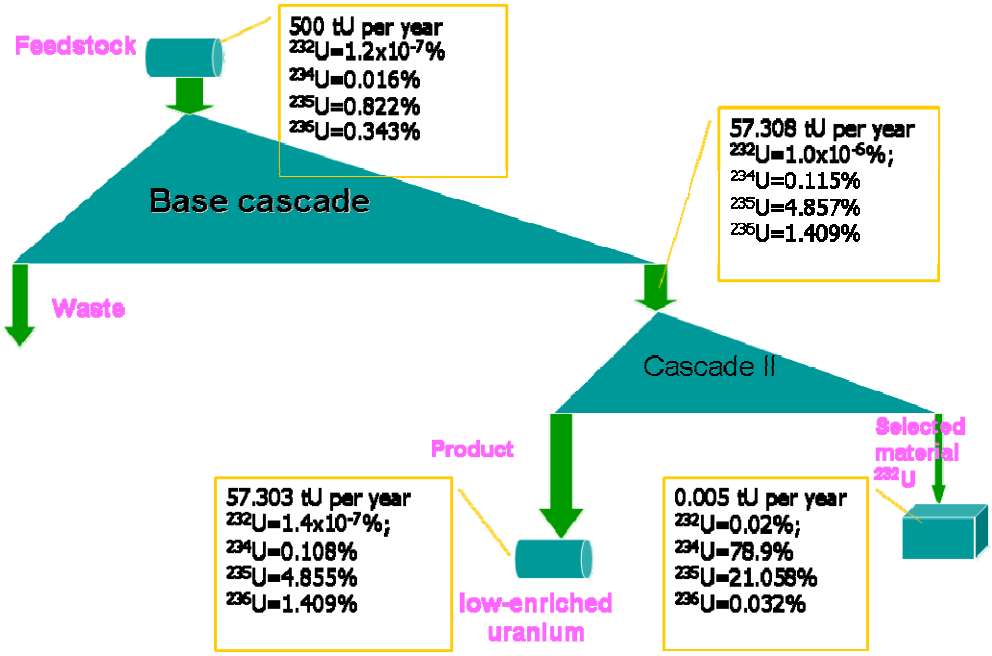

FIG. 1. Cascade for the purification of low enriched uranium from 232U.

The adverse effect of 232U in RepU can be reduced by using a centrifuge cascade to purify the material from 232U. The cascade flowchart is shown in Fig. 1. The Russian Federation evaluated the construction of such a cascade and demonstrated the possibility of its creation in principle.

The SGChE experts, in collaboration with the Rosatom experts, assessed the feasibility of creating a dual-purpose cascade designed to purify RepU from of ^{232}U and ^{236}U.

The idea stemmed from the assumption that, if RepU is enriched to high concentrations of ^{235}U (up to 90% and above), ^{236}U as a heavier isotope will go to the tails and therefore, purification from this isotope will take place. The next cascade performs after-purification of the obtained highly enriched uranium from ^{232}U, and waste material obtained from the second cascade is blended with a diluent (waste, feed or low enriched UF_6) in order to obtain low enriched uranium (LEU product). The cascade flowchart is shown in Fig. 2. Additional feasibility studies are required.

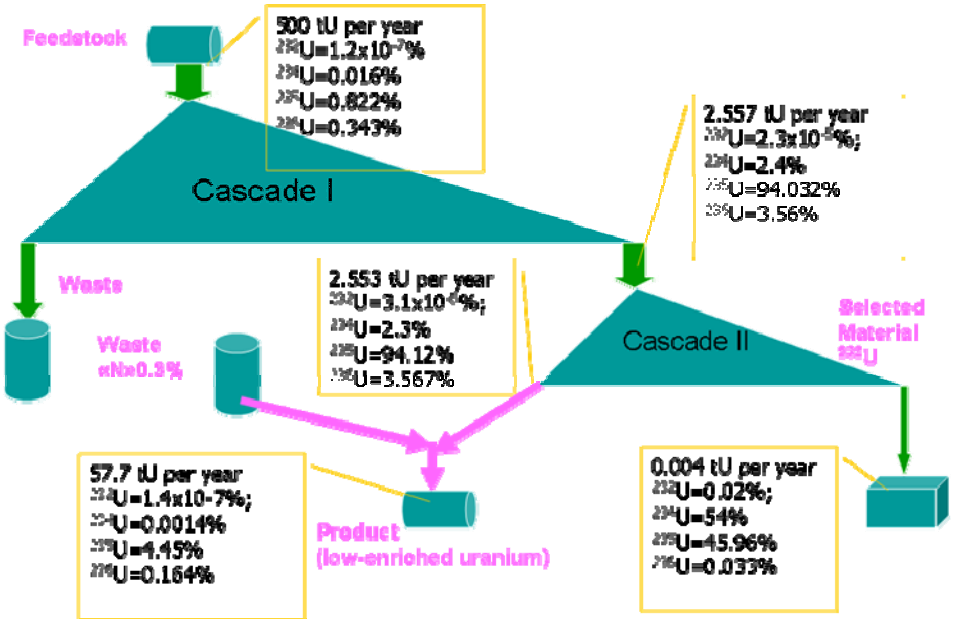

FIG. 2. Cascade for the purification of low enriched uranium from 232U and 236U

3. SGChE experience in reprocessed uranium treatment

The Federal State Unitary Enterprise 'Siberian Group of Chemical Enterprises' (SGChE) is a nuclear fuel cycle enterprise located in the center of South-Western Siberia, in the Tomsk region. It is an affiliate of the the Russian Federation's Federal Atomic Energy Agency.

The Enterprise has been engaged in nuclear technologies for decades. In August 2003, the Enterprise celebrated the 50th anniversary of the first production output which was enriched uranium at the enrichment plant.

Three fuel cycle facilities form the basis of the Enterprise: the radiochemical plant (RCP), the conversion plant and the enrichment plant.

3.1. Radiochemical plant

The radiochemical plant performs radiochemical processing of slightly irradiated spent fuel from two commercial SGChE-operated reactors with the production of RepU.

The plant also performs the radiochemical after-purification of reprocessed uranium oxides with up to 1% ^{235}U obtained from spent power reactor fuel in order to remove radioactive decay products accumulated in RepU, primarily ^{228}Th. Furthermore, the plant performs the purification of uranium from chemical impurities. Table 3 shows coefficients of purification from chemical impurities as well as from transuranic elements and fission products attained at the radiochemical plant.

TABLE 3. PURIFICATION COEFFICIENTS FOR CHEMICAL IMPURITIES, TRANSURANICS AND FISSION PRODUCTS ACHIEVED AT THE RADIOCHEMICAL PLANT

Element	Achieved Purification Coefficient	Element	Achieved Purification Coefficient
Al	>100	Th	>100
As	>150	Mo	>600
B	>300	Nb	>10
Be	>1	P	>20
Cd	>1	Si	>410
Ca	>69	Ta	>40
Cr	>1	Ti	>50
Cl	>6	V	>10
Cu	>10	W	>10
Fe	>400	Zn	>1
K	>160	Zr	>5
Mg	>3	Np	~ 100
Mn	>10	Pu	~ 1000
Ni	>1	^{99}Tc	>> 40
Na	>50		

All products obtained at the RCP in form of nitric acid uranium solutions are shipped to the conversion plant in order to further obtain uranium oxides and convert them into uranium hexafluoride (UF_6).

3.2. Conversion plant

The conversion plant performs the conversion of feed uranium with up to 1% ^{235}U into hexafluoride which is subsequently shipped to SGChE's enrichment plant or to other enrichment facilities. Initial stocks are nitric acid solutions of feed uranium from the radiochemical plant as well as natural uranium oxides or natural uranium tetrafluoride (UF_4) from outside customers.

3.3. Enrichment plant

The enrichment plant performs the enrichment of UF_6 up to 5% ^{235}U using gas centrifuge equipment. The plant is capable of enriching both natural and reprocessed uranium with the obtainment of products that are in line with the ASTM requirements for commercial enriched natural uranium (ENU) or enriched reprocessed uranium (ERU). A stand-alone cascade is available at the plant to enable the enrichment of RepU.

The enrichment plant's outputs are sold both to the domestic market and to the international market. The plant has been in the international enrichment services market since 1993.

SGChE has been engaged in the enrichment and processing of RepU virtually since its inception. However, for about 40 years the RepU processed at the enrichment plant was slightly irradiated uranium derived from spent commercial reactor fuel with burnups of only about 1000 MW•d/t U.

The first 100 tonnes of RepU derived from spent power reactor fuel with the burnups of about 30 000-35 000 MW•d/t U were processed at SGChE in the period 1988-1989. This material was used to meet the Russian nuclear power industry's requirements.

The treatment of RepU derived from spent power reactor fuel started on a constant basis in the early 1990s as part of international contracts for the recycling of RepU from France.

Figure 3 contains the scheme for processing reprocessed uranium as uranium oxide within SGChE. The processing technique involves three stages:

- radiochemical purification of initial oxides;
- conversion of purified oxides into hexafluoride; and
- enrichment of feed hexafluoride to 5% ^{235}U.

It is well known that one of the major problems associated with the chemical treatment of RepU is caused by ^{232}U that, after ^{228}Th, features a long chain of short-lived and, consequently, highly radioactive elements. In terms of radiative effects, the highest priority hazards in this chain are posed by ^{220}Rn (thoron) due to its possible emanation into the working air and by ^{208}Tl with its decay energy of 2.61 MeV inducing a considerable deterioration in the γ radiation environment.

The development over time of the ^{228}Th activity since the RepU's radiochemical purification is shown in Figure 4. The activity curve illustrates that if a time period between radiochemical purification of RepU and its subsequent treatment is reduced to less than 3 months, the RepU's ^{228}Th content will be less than 10% of the equilibrium value and, therefore, the ^{208}Tl impact on the staff will be minimized.

The radiochemical recycling of the French RepU in form of oxides at SGChE allowed to remove the ^{232}U decay products which had accumulated in the RepU due to its long-term storage prior to its further treatment in SGChE's facilities. In parallel with the removal of decay products, the RepU was after-purified from fission products, transuranic elements and ^{99}Tc. In addition, the radiochemical plant's equipment made it possible to produce enlarged isotopically homogeneous lots of 100-120 tonnes U that facilitated further enrichment of this feedstock in the enrichment cascade of the enrichment plant.

Purified oxides underwent conversion into UF_6 at the conversion plant. The UF_6 was shipped to the enrichment plant for its subsequent enrichment.

During the period 1992-1998, RepU totalling 1307.4 tonnes U delivered from France as uranium oxide were reprocessed according to this scheme.

Another RepU quantity of about 350 tonnes U was shipped in form of UF_6 from France to SGChE. It underwent direct enrichment at the enrichment plant. As the result of processing this feedstock, there was an increase in the radiation levels of the sublimation equipment at the enrichment plant. Besides, problems of returning shipper containers after feedstock sublimation arose as the bulk of the ^{228}Th being a non-volatile fluoride remained in the containers (‘heeled’ containers). For this reason SGChE prefers RepU feedstock to be shipped in form of oxides.

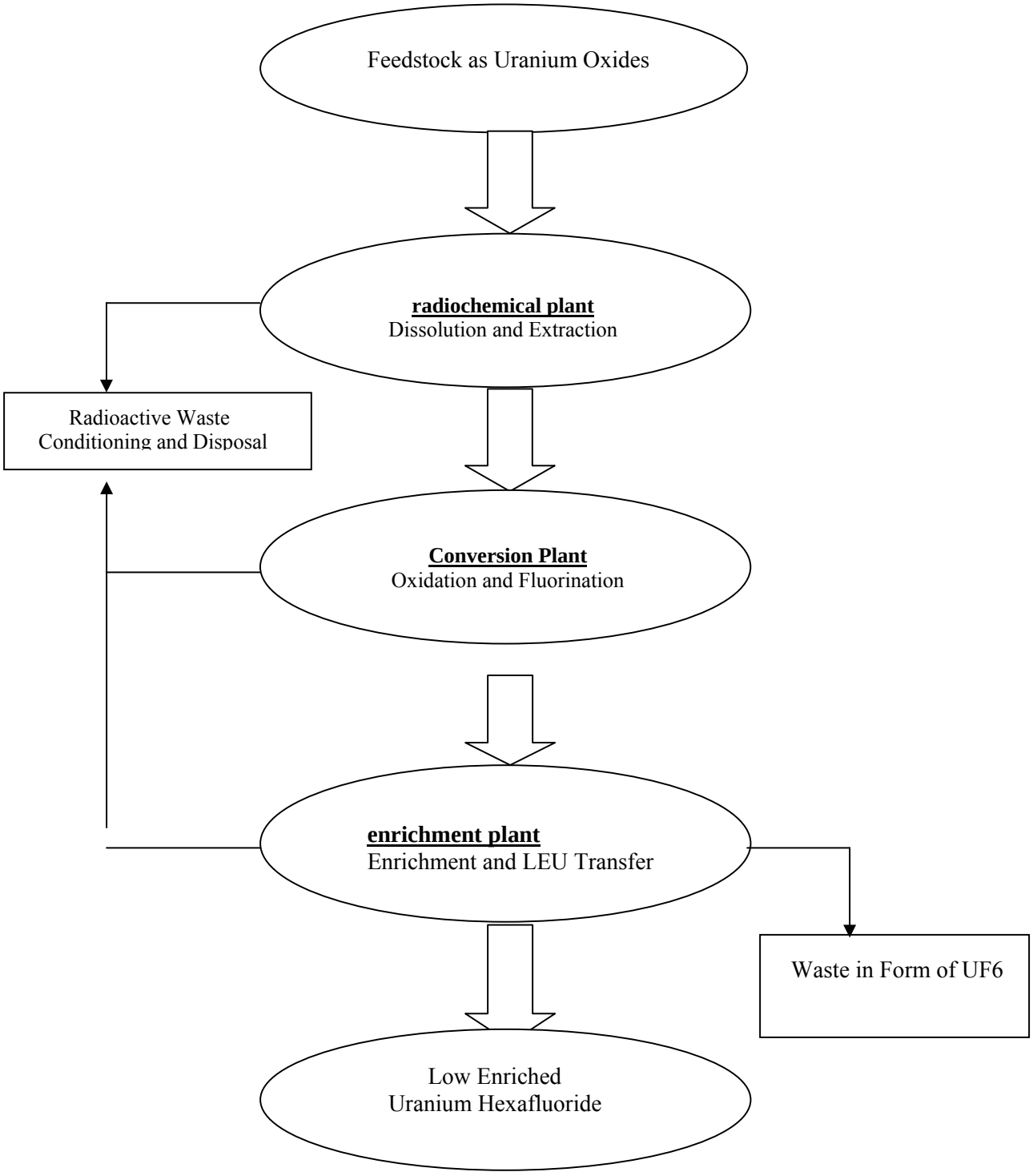

FIG. 3. Scheme for processing RepU feedstock at SGChE.

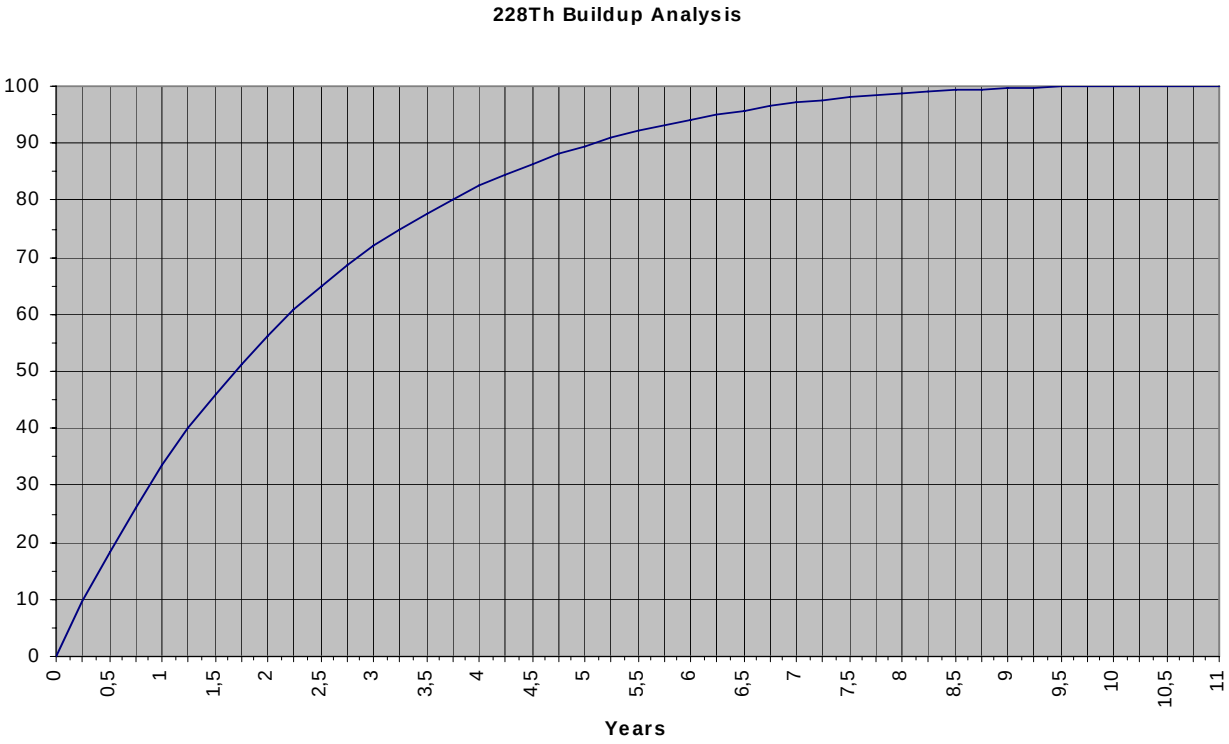

FIG. 4. ^{228}Th activity curve (in% of equilibrium value).

TABLE 4. ISOTOPIC COMPOSITION OF FRENCH REPU PROCESSED AT SGChE

Chemical Form of Feedstock	**Quantity (t U)**	**Isotopic Composition of Feedstock (% of U total)**			
		^{232}U	^{234}U	^{235}U	^{236}U
Hexafluoride	349.3	8.8×10^{-8}	0.0172	1.062	0.3374
Uranium oxide	1307.4	1.24×10^{-7}	0.0159	0.822	0.3427
Total uranium	1656.7	1.17×10^{-7}	0.0162	0.872	0.3416

The isotopic composition of the French RepU processed at SGChE is shown in Table 4.

As result of the direct enrichment of this feedstock at the enrichment plant, low enriched uranium hexafluoride with a ^{235}U content of 3.0-4.95% was obtained. The ^{232}U content in the end product therewith amounted to 1×10^{-6}%, the ^{234}U content up to 0.1%, and the ^{236}U content up to 1.4%.

Thus, the availability of three processing stages (radiochemical treatment, sublimation and separation) at SGChE allows to minimize interstage periods by RepU processing sequence scheduling and, therefore, to minimize the plant staff radiation load induced by fission products.

4. Estimation of future reprocessed uranium treatment at SGChE

Today, the world market witnesses trends which favourable for the recycling of all available RepU inventories into nuclear fuel cycle. Keeping in mind that this material was formerly obtained at relatively

low burnup levels, its isotopic composition enables the unlimited use of this RepU in processing and producing ERU fuel for nuclear power plants.

Capacities were created at SGChE to process annually up to ~ 1500 tonnes of RepU and to offer RepU enrichment services totalling about 1 million SWU.

These capacities are enough to cover the requirements of both domestic and foreign markets for the upcoming 5 to 10 years. If needed, these capacities can be expanded.

AREVA's experience and future project for reprocessed uranium management

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Abstract. AREVA has significant experience in managing reprocessed uranium (RepU) from reprocessing to the fabrication of enriched reprocessed uranium (ERU) fuel assemblies. In France, reprocessing facilities are located on two sites: at Marcoule (UP1 plant, South of France) and at La Hague (UP2 and UP3 plants, Normandy). Production in the UP1 plant was terminated at the end of 1997 after 40 years of operation. Since 1998, the plant has started its decommissioning program. The remaining 2800 tonnes of RepU stored at Marcoule should be processed before the end of 2009. As of today, the two operating plants located at La Hague (UP2-800 started in 1994 and UP3 started in 1990), can be considered as a single industrial platform that has a licensed capacity of 1700 t HM/year. The former UP2-400 plant which started in 1966 is now under decommissioning. In total, AREVA has separated more than 22 000 tonnes of RepU from light water reactor (LWR) spent fuel at La Hague (plus about 4600 tonnes of RepU from of spent gas-cooled reactor (GCR) fuel) and sent them to Pierrelatte in the uranyl nitrate hexahydrate (UNH) form for conversion into U_3O_8 or UF_6, according to the recycling routes chosen by RepU owners. The two de-nitrification facilities in Pierrelatte convert UNH into U_3O_8 to be stored prior to its future recycling. The conversion facility of Comurhex has converted reprocessed uranium from various customers since 1972. Two of those three facilities are scheduled to be shut down at the end of 2008, TU5 being the sole unit remaining in activity. The fabrication plant of FBFC at Romans has been manufacturing enriched reprocessed uranium (ERU) fuel assemblies since 1993. Based on its large experience of managing RepU, taking into account the technical constraints and the evolution of the characteristics of the recovered RepU, AREVA has a project to invest in various new units offering the totality of services necessary for the recycling of RepU: a new conversion facility; capability to directly enrich RepU (in form of UF_6) in the Georges Besse II enrichment facility; several other support facilities covering necessary services for the recycling of reprocessed uranium; logistics services.

1. Operational experience of RepU management at AREVA

1.1. Quantities of converted RepU

Over the years, AREVA has acquired a significant experience in the conversion of RepU from uranyl nitrate to oxides or fluorides. The ^{235}U assay was as high as 2.5%.

The Installation Nucleaire de Base (INB) 105 (St2000, St300, St2450) converted reprocessed uranium into UF6 since 1972. Three facilities, St2000, TU2 and TU5 have been converting uranyl nitrate coming from the Marcoule and the La Hague reprocessing plants into U_3O_8 for interim storage. The production of fluorides was shut down in 2006 because of non-compliance with regulations. St2000 and TU2 are scheduled to shut down at the end of 2008 based on the authorities' decision. TU5 will remain the only unit in operation.

Figure 2 displays the quantities of UF_6 and U_3O_8 which have been converted at Pierrelatte since the early 1970s.

FIG. 1. Emptying of uranium nitrate from LR65 tank containers at TU5 (left) and interim storage in P35 (right).

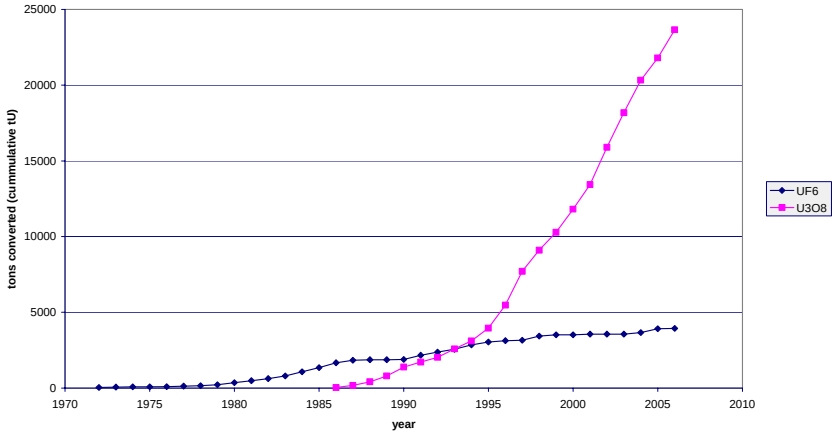

FIG. 2. History of conversion of RepU into UF_6 and U_3O_8 at Pierrelatte.

1.2. Experience in homogenization and purification of enriched UF6

The transfer workshop (TE) has been used since 1996 to carry out purification and homogenisation campaigns of RepU (in form of UF_6) and enriched RepU (in form of UF_6) prior to the delivery to the fuel fabricator (see Table 1.).

These transfers are important for two reasons in the recycling process:

- Firstly, the gaseous transfer from one 30B 'emitter cylinder' to another one eliminates the ^{232}U daughter products (strong gamma emitters) which remain in the emitter cylinder. This operation allows to deliver low irradiation cylinders to the fuel fabrication facility. The emitter cylinders showing high irradiation levels are then stored for a decay period and should be washed before reuse.
- Secondly, it allows to reduce dispersion of minor isotopes (^{232}U and ^{236}U principally) within the 30B cylinders containing the necessary quantity of enriched material for the fabrication of one ERU reload.

For enriched RepU, the level of ^{232}U was of a few ppb/U at the beginning and is nowadays reaching 15ppb/U or higher levels. This high level of ^{232}U leads to the implementation of irradiation shielding during the operations, close monitoring of personnel exposure and specific measures for handling and storage of emptied cylinders.

TABLE 1. HISTORY OF REPU CAMPAIGN AT TE WORKSHOP

Year	Campaigns	Quantity (tU)	U235 assay
1996	1	34.9	3.70
	2	23.9	3.70
	3	17.4	3.70
1997	1	17.6	3.70
1998	1	21.4	3.70
	2	20.1	3.95
	3	20.8	3.95
1999	1	16.5	3.95
2000	1	18.4	3.95
2001	1	17.8	3.95
2002	1	18.7	3.95
2003	1	18.3	3.95
	2	101.1	0.80
	3	25.5	3.95
2006	1	19.1	4.00

This stage has become of more significant importance with the increase of the ^{232}U level in reprocessed uranium as high levels of irradiation at the contact of the emitter cylinders containing heels are reached within a shorter period (10 mSv/h).

AREVA's experience also covers 48Y and 30 B cylinder management, namely storage, washing. However, the latter operation is no longer performed due to strong regulatory constraints.

2. The challenges of RepU recycling

2.1. UF6 conversion process

In Figure 3, the conversion process is detailed. After precipitation of ammonium di-uranate (ADU), the uranium material is calcined and reduced to UO_2. Hydrofluoration is performed using HF in rotating furnaces. The UF_4 is then converted to UF_6 in a flame reactor. Residues are finally burned in a plate reactor.

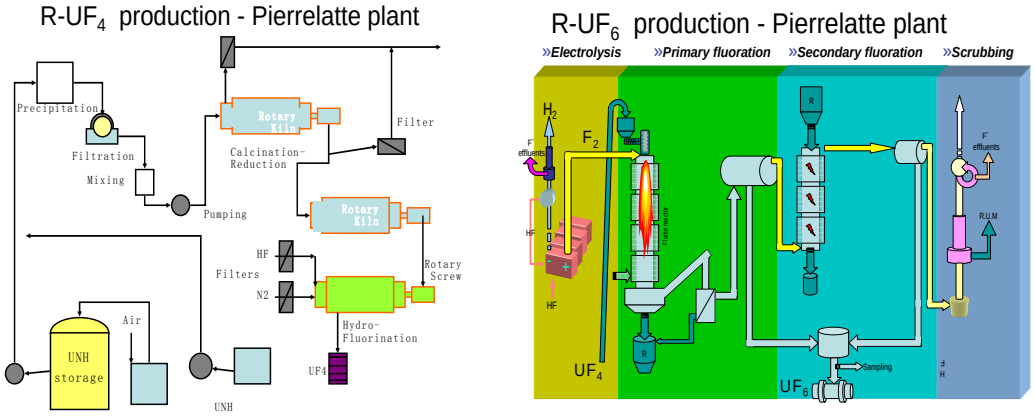

FIG. 3. Fluoride conversion process at Pierrelatte.

This process has proven very reliable over the years with a production of both high quality UF_4 and UF_6. On the long term, several issues had however to be addressed:

- *Minimization of waste*. With the precipitation of ADU using ammonia, a liquid effluent is produced which has to be treated before disposal. Also the excess F_2 which is not burned in the plate reactor creates CaF_2 sludge after treatment of the KOH scrubbing agent.
- *Handling of the residues*. Some impurities tend to concentrate in the residues, making them difficult to handle. Table 2 summarizes the properties of key impurities in the process.

TABLE 2. PROPERTIES OF VARIOUS ACTINIDES OR FISSION PRODUCTS

Element	Compound	Ebullition or sublimation point	Remarks	Potential issues
Pu	PuF_6	63°C	$PuF_6 + UF_4$ -----> $PuF_4 + UF_6$ $PuF_6 + NiF_2$ -----> PuF_4 . $NiF_2 + F_2$	for ashes treatment
Np	NpF_6	54°C	NpF_6 is more volatile and stable than PuF_6 $NpF_6 + UF_4$ -----> $NpF_4 + UF_6$	for ashes treatment and for UF6 quality
Tc	TcF_6 TcF_5 $TcOF_4$ $TcOF_3$	55°C melts at 50°C - decomposes at 200°C 165°C 100°C	All compounds are volatile Tc99 is difficult to predict during enrichment	for UF6 quality
Ru	RuF_5 RuF_6 $RuOF_4$	230°C à 270°C decomposes in RuF_5 at 200°C 180°C	All compounds are volatile but Ru 106 has often decayed and is in low level in UNH	
Sb	SbF_5 SbF_3	140°C sublimes at 200°C	As for Arsenic and Technetium, antimony can be problematic. However Sb125 is present in UNH at very low level	
Th	ThF_4	non volatile (melts above 900°C)	daughters of Th will accumulate in residues	for ashes treatment and for UF6 fabrication

As thorium isotopes (^{234}Th and ^{228}Th) do not yield volatile fluorides and as they have daughters of relatively short life time, a high irradiation level at the plate reactor may arise. Typically 1-2 mSv/h can be found at contact of the plate reactor and 10-20 mSv/h at contact of the drums collecting ashes.

- *Treatment of ashes from the plate reactor*. In such materials the actinide level may be very variable depending on the quality of the UNH and the F_2 excess during fluorination. For example for ^{237}Np it may be as high as 15 000Bq/gU. A special facility must be designed to recover and purify the uranium present in the ashes.

2.2. Lead time and irradiation levels

Throughout the whole process of RepU recycling, time constraints are a key parameter to limit the irradiation due to decay products of ^{232}U. With the increase of burn-ups of used UOx fuels and, accordingly, increased ^{232}U levels in the reprocessed uranium, the time constraint is reinforced.

Back in the 1990s, the average ^{232}U level in RepU before enrichment was 1.0 ppb/U and the alpha activity of the daughters reached 1670Bq/gU some 19 months after purification at La Hague. Today, the ^{232}U level has risen to an average of 1.8 ppb/U in RepU, and in 2020 it may reach 3.5 ppb/U. With such material, the activity of 1670Bq/gU will be obtained in only 4 months.

Irradiation measures performed on 'heeled' RepU 48Y and 30B cylinders (emptied UF_6 cylinders still containing all impurities which are not UF_6) after emptying has allowed AREVA to simulate the expected irradiation level of cylinders depending on the age of the product and the ^{232}U level. This

modelling will allow to optimise the whole programming of ERU fuel manufacturing, taking into account units specifications as well as logistics services needed across the recycling process.

A fleet of cylinders required will need to be washed before reuse. This operation is one of the challenges for a sustainable large scale RepU recycling solution.

3. AREVA's RepU recycling project

In order for AREVA to meet its customers' needs and requirements, it has developed a complete and integrated solution for the recycling of RepU on an industrial scale.

In the current context of highly volatile and rising market prices of natural uranium, recycling uranium processed from spent fuel is becoming increasingly attractive. It allows utilities to secure supplies of fissile material in the medium term.

AREVA's is designed to give its customers integrated and customised solutions for recycling existing stockpiles of RepU (in oxide form) as well as fresh RepU coming from La Hague.

The project will handle every necessary steps of the RepU recycling process, thus achieving sustainable development objectives:

- RepU conversion complex;
- RepU enrichment capacities in the 2nd unit of the Georges Besse II enrichment plant (Unat/RepU mixed unit);
- purification/ homogenisation of the enriched UF_6 before delivery to the fuel fabricator;
- defluorination of tails and storage under oxides form;
- management of 48Y and 30B cylinders (washing, re-certification, storage).

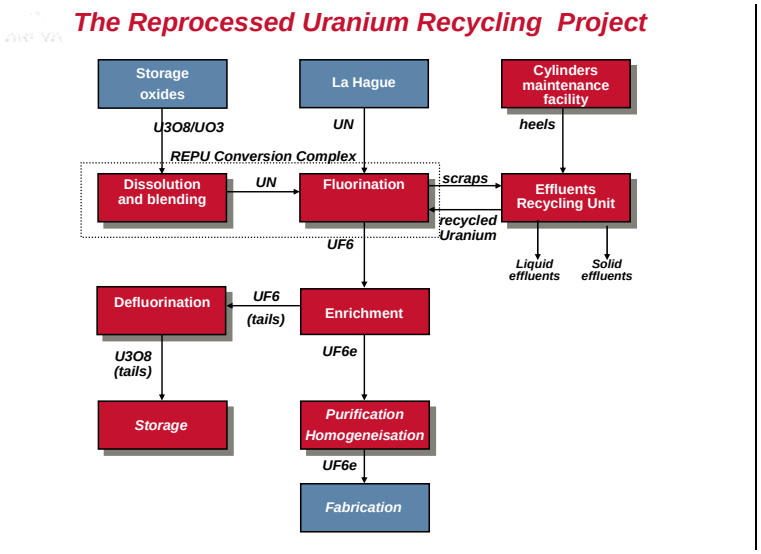

FIG. 4. The RepU recycling project.

The new facilities will be designed to comply with the most stringent standards of nuclear safety taking into account the latest regulatory constraints. The evolution of the characteristics of the RepU stemming from used UOx fuel, i.e. increased concentration of minor isotopes (^{232}U, ^{234}U and ^{236}U) due to higher burn-ups, has been anticipated and integrated in the design data to overcome today's limitations and constraints and to offer a long-term basis capability to manufacture ERU fuel.

Based on expertise capitalised during its 35 years of experience of RepU management, the facilities will integrate both mature proven technologies and innovative processes developed by AREVA's R&D Department. The objectives are to achieve high quality and productivity levels while limiting personnel exposure and dose rates as well as to reach high standards for environmental protection. The project will include the following improvements:

- *Thermal denitration* of the UNH (instead of ammonia precipitation). This patented process produces highly reactive UO_3 and avoids generation of liquid effluent. Moreover, HNO_3 will be recovered from the gaseous stream and recycled in the process.
- *Scraps and effluent treatment* with a dedicated facility called SRU.

AREVA's R&D Department is also conducting programs to minimize wastes from the fluorination process (minimize CaF_2 sludge, optimise secondary fluorination reactor).

The recycling facilities will be integrated on the Tricastin site. Thus, AREVA's RepU recycling project will allow to optimise the lead time of the ERU fuel manufacturing process, thereby reducing irradiation/exposure levels throughout the operations. It will also minimise external transportation.

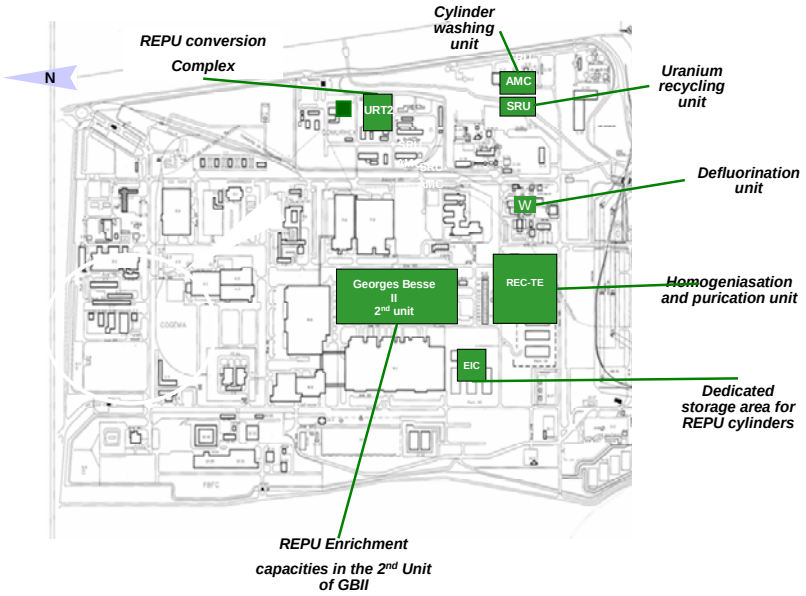

FIG. 5. Overview of RepU recycling project facilities layout.

Reducing lead times when handling RepU is a key factor in enabling:

- operations to be performed in accordance with ALARA principles;
- limit any additional steps becoming compulsory due to aged products; and
- optimisation of transportation services as well as logistics constraints.

4. Conclusion

Recycling both uranium and plutonium is a condition for the sustainable nuclear renaissance.

When customer commitments to recycle significant RepU quantities on a long-term basis materialise, AREVA will operate the appropriate facilities on the Tricastin site. The fully integrated RepU recycling project will offer controlled and competitive conditions for tailored made RepU recycling solutions for fuel cycle customers.

Reprocessing of spent nuclear fuel at the PA 'Mayak' and reprocessed uranium using

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Abstract. The paper describes briefly experience of spent nuclear fuel reprocessing at RT-1 reprocessing plant and reprocessed uranium handling including foreign origin uranium (from COGEMA). Some current issues are reflected in this paper namely connected with increasing of NPP nuclear fuel burnup mainly. Methods of uranium isotopic composition control are given in the paper as well as methods which can be used at Production Association at Mayak (PA 'Mayak') in future are presented.

1. Introduction

PA 'Mayak' was founded in 1948 within the framework of the former Soviet Union's defence program. It is located in the Urals, in the Chelyabinsk region. Nowadays, PA 'Mayak' is a big complex of industrial plants and production departments. The enterprise management is consolidated.

The first Russian reprocessing facility, known as RT-1, was started on the radiochemical plant base in 1977. Nowadays, RT-1 remains the only reprocessing plant in the Russian Federation.

The fact is that at present there is full-scale reprocessing in France, the United Kingdom and the Russian Federation. All these reprocessing facilities use similar technological processes, such as water pool storage of spent nuclear fuel (SNF), shearing of fuel rods, nitric acid dissolution of the fuel, extraction of uranium and plutonium by means of the PUREX (plutonium and uranium recovery by extraction) process, vitrification of high level wastes (HLW), etc. However, each enterprise has its own technological features, which are sometimes very different from the others.

2. Features of the RT-1 reprocessing facility

The main feature of RT-1 is reprocessing of broad spectrum of spent nuclear fuels. The following spent fuel types are reprocessed:

SNF from pressurized water reactors (PWR) (WWER-440) and fast breeder reactors (FBR) (BN-600):

- SNF from transport ship reactors;
- SNF from production reactors; and
- SNF from research reactors.

As mentioned above, the world-known technological processes are used at RT-1. Nevertheless, there are some distinctive features of the technologies used at RT-1:

- Universality of the three technological lines which allows not only to reprocess various SNF kinds, but also to realize the joint reprocessing of different SNF types.
- Achievement of the target enrichment of recycled uranium by mixing uranium gained by the reprocessing of *various* kinds of SNF.

- Extraction of various elements (such as caesium, strontium, promethium, etc.) which are used for radioisotope production.

The general technological scheme of SNF reprocessing at RT-1 is shown in Fig. 1.

The following describes the basic technological processes for the handling and processing of the spent nuclear fuel.

The ***shipment of SNF*** is accomplished by the railway with certified transport packages.

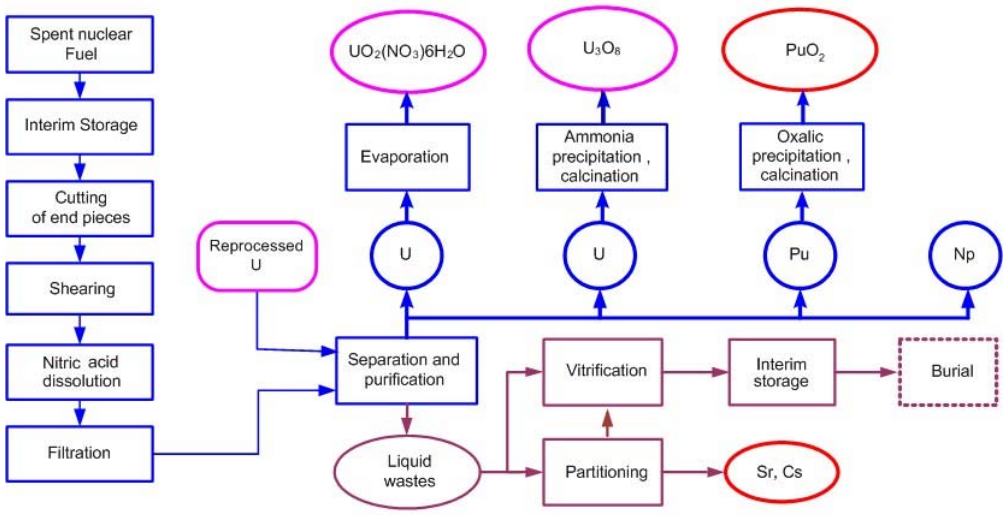

FIG. 1. General technological scheme of SNF reprocessing at RT-1.

Transport packages delivered to the plant are unloaded in a hot cell by 'dry' way. The SNF is then stored in the water pool. The water layer of more than three meters height provides reliable radiological protection to the operating staff. As a rule, the period of ***interim water pool storage*** of spent nuclear power plant (NPP) fuel is up to 5 years.

The first stages of ***reprocessing*** operation are the cutting of the end-pieces and the shearing of spent fuel assemblies into pieces with a length of less than 60 mm. Thereafter, fuel materials from these pieces are dissolved by nitric acid in a cycling dissolver. After filtration the dissolved material is separated by the PUREX process into uranium, plutonium and neptunium solutions, and liquid radioactive wastes.

The RT-1 technological scheme allows the simultaneous reprocessing of different kinds of SNF by the three technological lines, with the further mixing of uranium solutions in order to achieve the necessary enrichment. The target enrichment is provided by mixing uranium from the reprocessing of spent light water reactor (LWR) fuel (WWER-440) with highly enriched SNF, for example SNF from FBRs (BN-600) or SNF from research reactors.

The target products after the reprocessing are:

uranium nitrate hexahydrate (UNH), obtained by evaporation of nitric acid uranium solution with an enrichment of no more than 3.1% ^{235}U;
highly enriched U_3O_8 obtained by means of ammonia precipitation and calcination; and
plutonium dioxide (PuO_2) by oxalic precipitation and calcination.

At present, all reprocessed uranium is used for nuclear fuel production. Extracted plutonium is placed into special storage; in future it should be used for MOX fuel production.

Besides the above mentioned products, the technological process provides the extraction of neptunium and iodine for their isolation. Furthermore, krypton (^{85}Kr), strontium, cesium, americium, promethium and other radionuclides are extracted for radioisotope production.

3. Potentialities of reprocessed uranium purification

Besides spent nuclear fuel reprocessing, the technological scheme of RT-1 allows to purify previously reprocessed uranium with a ^{235}U enrichment of no more than 3.1% by means of a single or double extraction process.

Table 1 displays the quality of uranium purification by the example of one of the reprocessed uranium consignments.

In the period 1989-1990, approximately 600 t of RepU from COGEMA was purified and enriched at RT-1 (by mixing it with material with a higher ^{235}U content). The resulting uranium was supplied for nuclear fuel production in the Russian Federation.

TABLE 1. QUALITY OF URANIUM PURIFICATION OF A PARTICULAR REPU CONSIGNMENT

Element	**Percentage**
Al	1×10^{-4}
B	1×10^{-5}
Cd	1×10^{-5}
Ca	1×10^{-3}
Cr	1×10^{-3}
Cl	2×10^{-3}
Cu	1×10^{-4}
Fe	1×10^{-3}
K+Na	5×10^{-3}
Mg	1×10^{-3}
Mn	1×10^{-4}
Ni	1×10^{-3}
Mo	1×10^{-4}
P	2×10^{-3}
Si	1×10^{-3}
V	1×10^{-4}
W	1×10^{-4}
Pu	$< 10^{-7}$

Radioactive Nuclide	**Specific Activity (Bq/kg U)**
^{106}Ru	4×10^{5}
^{228}Th	8×10^{4}
^{234}Pa +^{234}Th	1×10^{7}
^{137}Cs	1×10^{3}
^{95}Zr	7×10^{2}
Specific kerma-equivalent, nGy·m^2/s	7×10^{-3}

4. Reprocessed uranium realization

At present, PA 'Mayak' supplies reprocessed uranium to JSC TVEL for the production of NPP fuel at the Ulba Metallurgical Plant (UMZ). The rate of recent selling is shown in Figure 2.

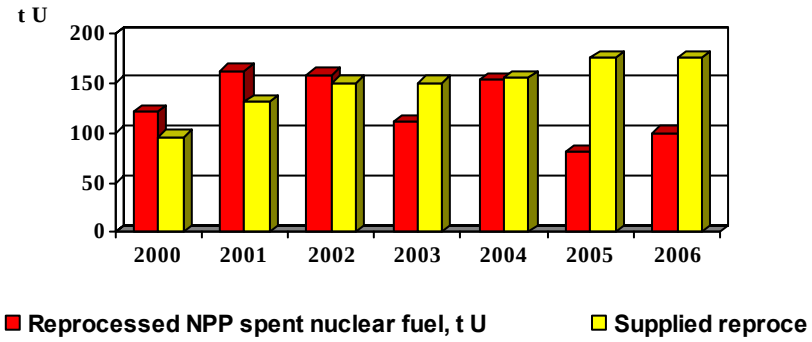

FIG. 2. Spent nuclear fuel reprocessed at RT-1 and RepU supplied to JSC TVEL for NPP fuel production, 2000-2006.

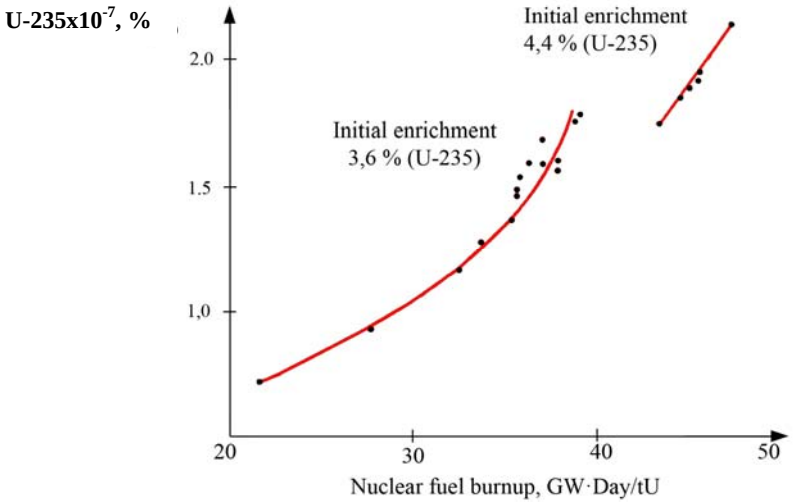

FIG. 3. Dependence of the U-235 content on the nuclear fuel burnup of WWER-type reactors.

According to Fig. 2, uranium sales were pretty steady throughout the period 2000-2006. Nevertheless, some increase of the supply volume (up to 175 t per year) has taken place since 2005. Since 2007, the enrichment of supplied uranium has been increased from 2.6% to 3.1% ^{235}U.

The important issue is the management of even uranium isotopes, and especially of ^{232}U. The content limit of this isotope is 2.2×10^{-7}%. This limit is determined by radiation environment limits at the nuclear fuel manufacturer (UMZ). It is a difficult problem in view of nuclear fuel burnups rising to 50-55 GWd/t HM. The quantitative dependence of the ^{232}U content on the nuclear fuel burnup of WWER-type reactors is shown in Figure 3.

At present, the necessary isotopic composition of supplied uranium is obtained by involving in the reprocessing both high- and low-burnup SNF or by the addition of reprocessed uranium with low ^{232}U contents. The time history of the mean ^{232}U content in supplied uranium is given in Table 2.

TABLE 2. HISTORY OF THE MEAN ^{232}U CONTENT IN SUPPLIED URANIUM

Year	Mean ^{232}U Content (10^{-7} %)
2000	1.08
2001	1.14
2002	1.33
2003	1.62
2004	1.86
2005	1.96
2006	1.99

Figure 4 shows the uranium flow scheme with some qualitative assessment. This scheme allows achieving the necessary isotopic composition of the currently supplied uranium. Table 3 shows the isotopic composition of one of the supplied batches.

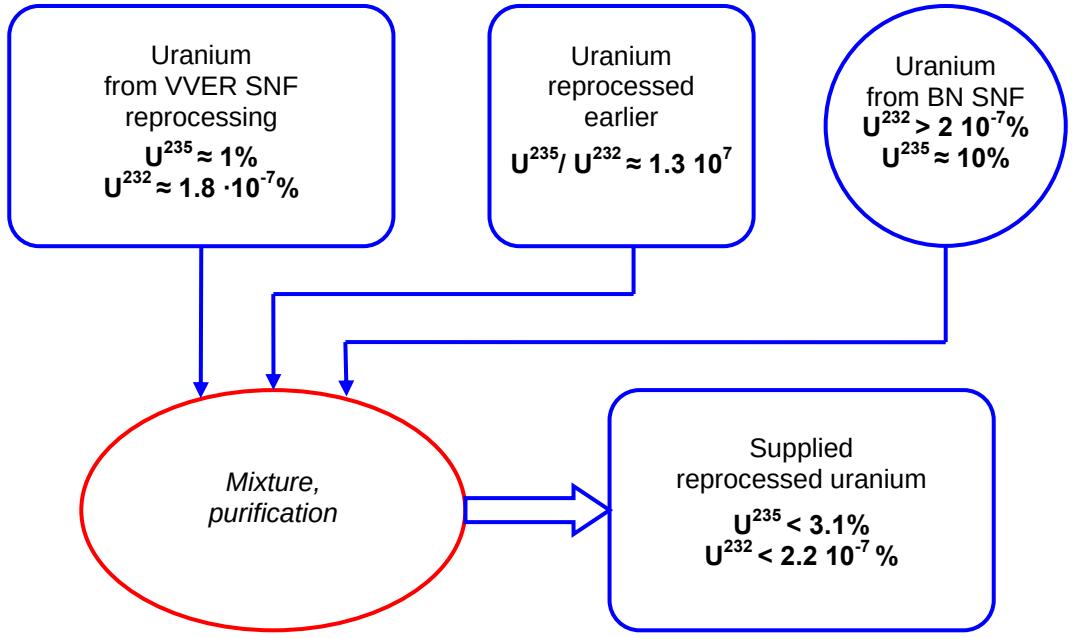

FIG. 4. Uranium flow scheme in the RT-1 plant of PA 'MAYAK'.

TABLE 3. TYPICAL ISOTOPIC COMPOSITION OF ONE OF THE URANIUM BATCHES SUPPLIED BY THE RT-1 PLANT

Isotope	Content (%)
^{232}U	1.71×10^{-7}
^{234}U	0.034
^{235}U	2.91
^{236}U	0.56

The ^{236}U isotope captures neutrons. This effect should be compensated by increasing the ^{235}U content in nuclear fuel. The ^{236}U percentage in high-burnup LWR SNF may reach 0.7-0.8%.

Evidently, the uranium flow scheme used at RT-1 (see Figure 4) has some limitations. Therefore, in future other approaches should be employed, such as the following:

- Increasing the limit for the ^{232}U content on the condition of taking additional measures for personal radiation protection in the nuclear fuel production enterprises. For example, the duration of the interim storage of RepU and the fuel fabricated thereof may be reduced.
- Involving into reprocessing the previously spent nuclear fuel with low burnup (as temporary measure).
- Usage of natural uranium for isotope composition management. In case of RT-1, this is a very effective method to control the even uranium isotopes in supplied uranium.

Table 4 gives an example of the calculation of the isotope composition of obtained RepU to which natural uranium was added.

TABLE 4. EXAMPLE OF THE ISOTOPE COMPOSITION OF OBTAINED REPU TO WHICH UNAT WAS ADDED

Component	**Isotope Composition**			**Share (%)**
	^{232}U (10^{-7} %)	**^{235}U (%)**	**^{235}U (%)**	
Reprocessed uranium from LWR SNF	2	0.45	0.99	61
Natural uranium	-	-	0.71	17
Reprocessed uranium from highly enriched SNF	4	1.5	10	22
Supplied reprocessed uranium	2.11	0.61	2.95	100

5. Conclusion

Concerning RepU management, the PA ‘Mayak’ enterprise features the following characteristics:

- It is able to supply RepU in the form of uranyl nitrate hexahydrate.
- The plans for the reprocessing of highly enriched SNF determine the production capacity of uranium enrichment.
- At present, the production at PA ‘Mayak’ focuses on the domestic consumers.
- Currently, all reprocessed uranium is used for the nuclear fuel production.

Reprocessed uranium experience on conversion and enrichment in Japan

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Abstract. Japan is poor in uranium resources. This is why reprocessed uranium (RepU) arising from spent fuel at reprocessing plants is a valuable energy sources. The research and development of the conversion process for RepU has been conducted by Japan Atomic Energy Agency (JAEA) since the 1970s. This paper introduces the achievements obtained from a series of tests.

1. Introduction

Domestic uranium resources are small in Japan. Therefore, the development of technologies to recycle RepU arising from spent fuel at reprocessing plants is indispensable to the reuse of RepU as nuclear fuel. In order to establish the closed nuclear fuel cycle for Light Water Reactors (LWR), it is essential to have technologies for RepU.

JAEA has been thinking about four different methods for the reuse of RepU: the re-enrichment of the material, its usage as uranium-plutonium mixed oxide (MOX) fuel, the mixing of RepU with depleted uranium, and the storage of RepU. The re-enrichment of RepU with the established enrichment technology is a relatively attractive method for JAEA. That is why JAEA decided to start developing the conversion technology which precedes the enrichment of RepU.

The feed material (RepU in the form of UO_3) has been transported from the Tokai reprocessing plant to the Ningyo-toge conversion plant where it was converted into uranium hexafluoride (UF_6). When the use of RepU in domestic commercial plants is taken into consideration, safety assessments of RepU are required. Hence, the projects outlined in this paper aim at the development of a conversion process and the acquisition of technical and economic date needed for the design and construction of a commercial conversion plant.

2. Object

JAEA had three approaches to develop the conversion technology for reprocessed uranium in the conversion facility at Ningyo-toge.

2.1. Small-scale test (1982-1987）

The UO_3 particles arising from the de-nitration of RepU in the form of uranyl nitrate hexahydrate (UNH) at the Tokai reprocessing plant are solid and their surface is very smooth. JAEA designed a small-scale facility with a 10 moles/h capacity on the basis of preliminary test results performed in the Tokai Works, where the behaviour of radioactive impurities was studied.

The purposes of the conversion study were as follow:

- Improvement of the chemical reactivity of UO_3:

- Testing and improving the operating conditions:
- Testing the behavior of the transuranic (TRU) and fission product nuclides.

The converted UF_6 was utilized for JAEA's enrichment studies. Approximately 1.3 t U (RepU in form of UF_6) which was before converted in the facility was sent to the Tokai Works and further 2.3 t U (RepU in form of UF_6) was used in the uranium enrichment facilities on-site at Ningyo-toge.

2.2. Middle-scale test (1987-1990）

Based on the results of the small-scale test, JAEA designed a larger facility with a 140 moles/h capacity the size of which is about one fifth of the practical plant. The middle-scale test was carried out to demonstrate the feasibility of the process and to confirm the operational safety of the plant. The purposes of the tests with batch process operations were as follows:

- Establishment of capability;
- Study of the effects on the hydration process;
- Study of the radioactive impurities in RepU;
- Development of analytical methods for the impurities;
- Safety analysis to handle RepU.

The converted UF_6 was enriched in the demonstration enrichment plant on-site at Ningyo-toge.

2.3. Practical application study (1994-1999)

As JAEA has acquired successful results from the middle-scale test, they decided to make the overall evaluation of the conversion technology for RepU. Therefore, key components of the Uranium Conversion Test Facility were dismantled and installed in the Refining and Conversion Pilot Plant to make a continuous process line.

The purposes of the studies were as follows:

- Assessment of reliability, safety and cost performances of the present RepU conversion;
- Acquisition of technical data for a future conversion plant;
- Reduction of radioactive wastes.

The converted about 29 t U as UF_6 was enriched in the uranium demonstration plant on-site at Ningyo-toge. The used RepU storage vessels are listed in Table 1.

TABLE 1. THE TYPE OF REPU STORAGE VESSELS

Process		**Storage Vessel**	**Maximum Filling Weights**
Conversion	Feed	UO_3 vessel	260 kgUO_3/vessel
	Product	48Y cylinder	12 501kgUF_6/cylinder
Enrichment	Feed	48Y cylinder	12 501kgUF_6/cylinder
	Product	30B cylinder	2277 kgUF_6/cylinder
Reconversion Feed		30B cylinder	2277 kgUF_6/cylinder

2.4. Results

2.5. Practical application study (1994-1999)

The developed dry conversion process for UO_3 is shown in Fig. 1.

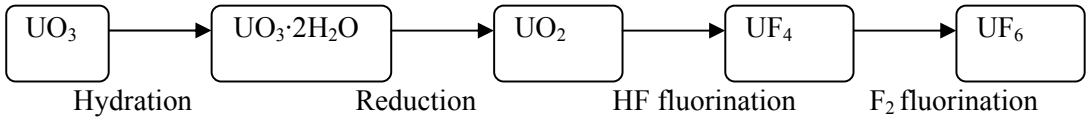

FIG. 1. The diagram of JAEA's conversion process.

The hydration method was proved very important for the improvement of the UO_3 particle reactivity, as shown in Fig. 1. Without hydration, JAEA suffered from converting a UO_2 particle to a UF_4 particle with incomplete conversion reactivity, as shown in Fig. 2.

The operating conditions from the practical application test are shown in Table 2.

TABLE 2. OPERATING CONDITIONS FOR REPU CONVERSION PROCESS

Process	**Reactor**	**Temperature (°C)**	**Mole Ratio**	**Duration (hours)**
Hydration	Pug mill	40	2.1 +/- 0.1 (H_2O/U)	3.3
Reduction	Fluidized bed reactor	550	2.0 (H_2/U)	4.7
HF fluorination	Fluidized bed reactor	400	1.1 (4HF/U)	8.0
F_2 fluorination	Flame reactor	430	1.2 (F_2/U)	0.4 sec
	Fluidized bed reactor	430	1.0 (F_2/U)	–

2.6. Specifications

2.6.1. Design of RepU components in the UO3

The different elements contained in RepU greatly influence the safety assessment for handling RepU itself. The following steps were taken regarding the licensing of a conversion facility by the Japanese regulatory bodies:

- Step 1: The calculations using the ORIGEN2 code for RepU components with the following operational condition at Tokai reprocessing plant:
  - Average burn-up: Less than 28 000 MW•d/t HM
  - Initial enrichment: Less than 4 wt% ^{235}U
  - Cooling time: More than 180 days
- Step 2: The survey of the calculating parameters for the safety assessment of RepU nuclides;
- Step 3: The decision for the calculating parameters conditions given in Table 3;
- Step 4: The performance by calculating parameters given in Table 3 for the RepU nuclides;
- Step 5: The decision of the nuclides in RepU for safety assessments;
- Step 6: The decision of the RepU composition.

TABLE 3. CALCULATING PARAMETER CONDITIONS FOR SAFETY ASSESSMENT OF REPU

Calculating parameters	Actinide isotopes		Fission Products
	^{232}U Series	others	
Average burnup	28 000 MW•d/t	28 000 MW•d/t	28 000 MW•d/t
Specific thermal power	15 MW/t	40 MW/t	40 MW/t
Initial enrichment	2.5% ^{235}U	4.0% ^{235}U	4.0% ^{235}U
Cooling time	13 years	13 years	180 days
Time after reprocessing	11 years	11 years	180 days

2.6.2. Licensed values of RepU

The values on the enrichment and re-conversion facilities are based on the results of the conversion operation.

TABLE 4. LICENSED VALUES OF REPU FACILITIES

		Conversion at Ningyo-toge	Enrichment at Ningyo-toge	Re-conversion in Japan	
				Type-1	Type-2
	Nuclides	Limited values			
Uranium			0.9%		
	^{235}U	≦ 1.3%	≦^{235}U≦1.3%		
	^{232}U	≦ 1.8 ppb	≦ 1.2 ppb	≦ 10 ppb	
	^{234}U		≦0.027%		
	^{236}U		≦0.4%		
(Bq/gU)	U(α)			≦3.6×10^{5}	≦3.3×10^{5}
TRU	Np(α)	≦ 66.7	≦ 9.6×10^{-2}		
(Bq/gU)	^{237}Np			≦1.0×10^{-1}	
	Pu(α)	≦ 5.61	≦1.0×10^{-1}	≦1.0×10^{-1}	
	Pu(β)			≦9	≦3
	Am(α)	≦ 33.3	≦3.2×10^{-1}		
	Cm(α)	≦ 33.3			
FP	^{95}Zr	≦ 37.0			
(Bq/gU)	^{95}Nb	≦ 37.0	≦1.3×10^{1}		
	^{99}Tc			≦14	≦10
	^{106}Ru	≦ 194	≦1.0×10^{2}	≦20	≦10
	^{125}Sb	≦ 37.0			≦ 2
	^{137}Cs	≦37.0			
	^{144}Ce	≦ 37.0			

2.7. Analytical measurements

2.7.1. Analytical method

The radioactive impurities in RepU arising from the Tokai reprocessing plant have never been detected by the regular method. Hence, the development of the advanced analytical method was needed to obtain the decontamination factor through the conversion process. Both the regular and the advanced method are shown in Table 5.

TABLE 5. ANALYTICAL METHODs FOR REPU

Nuclides	Analytical method		Lower limits (Bq/gU)
	Regular methods	Advanced method	
^{237}Np	TTA-Solvent extraction → α-spectrometry	TTA-Solvent extraction Anion exchange → α spectrometry	
^{238}Pu,^{239}Pu,^{240}Pu	TTA-Solvent extraction → α spectrometry	TTA-Solvent extraction Anion exchange → α spectrometry	$10^{-4} – 10^{-5}$
^{241}Am, ^{244}Cm		Anion exchange TOPO-Solvent extraction → α spectrometry	
^{106}Ru	γ spectrometry	Oxidize distillation → β spectrometry	$10^{-4} – 10^{-5}$
^{99}Tc	Distillation, Ion exchange → β spectrometry	Oxidize distillation Anion exchange → β spectrometry	10^{-2}
^{95}Zr,^{95}Nb,^{125}Sb,^{137}Cs, ^{144}Ce		Anion exchange → γ spectrometry	$10^{-4} – 10^{-5}$
^{232}U	Ion exchange → α spectrometry		
^{234}U,^{235}U, ^{236}U,^{238}U	Thermal ionization mass spectrometry		

2.7.2. Measurements of RepU

2.7.2.1. Uranium isotopic composition

In this conversion process, about 30 UO_3 vessels are needed to fill a 48Y cylinder, as shown Table 1. The homogeneous tank involved a filled 48Y cylinder which was heated with steam to liquidize UF_6 and homogenize ^{235}U concentrations in the 48Y cylinder.

The typical uranium isotopic compositions that JAEA measured are shown in Table 6.

TABLE 6. TYPICAL URANIUM ISOTOPE COMPOSITION OF REPU IN THE STORAGE VESSEL

Nuclide	UO_3 Vessel	48Y Cylinder	30B Cylinder
^{232}U	0.85 ppb	0.59 ppb	< 10 ppb
^{234}U	0.0016 wt%	0.0016 wt%	0.073 wt%
^{235}U	1.045 wt%	1.046 wt%	4.440 wt%
^{236}U	0.278 wt%	0.269 wt%	0.881 wt%

2.7.2.2. Decontamination factors of radioactive impurities

The following decontamination factors were obtained by the method described in Table 5: For Np: > 2.5×10^3; for Pu: > $10^{3;}$ for Am: > 10^3; and for Ru: > 29.

The decontamination factors of other nuclides were not obtained due to no detection. The decontamination factor (DF) is defined as follows:

DF = (the analytical value of the objective nuclide in UF_6)/(the analytical value of the objective nuclide in UO_3)

2.8. Corrosion against HF or F2 gas with high temperature

The reactor materials using high temperature HF or F_2 gas are important to design the future conversion plant. The corrosion rates on two fluidised beds and the flame-tower reactor in the HF and F_2 conversion process were measured with the ultra-sonic thickness equipment. The results are that the acquired maximum corrosion rates are 0.456 mm/year at 450 degrees (^{0}C) surrounded by 100% F_2 gas, as shown in Fig. 3.

2.9. Dose effects on the surface of UO3 vessels and UF6 cylinder

Measured dose rates on the surface of a UO_3 vessel and a UF_6 cylinder are shown in Figures 4 and 5. All date are lower than preliminary evaluated values.

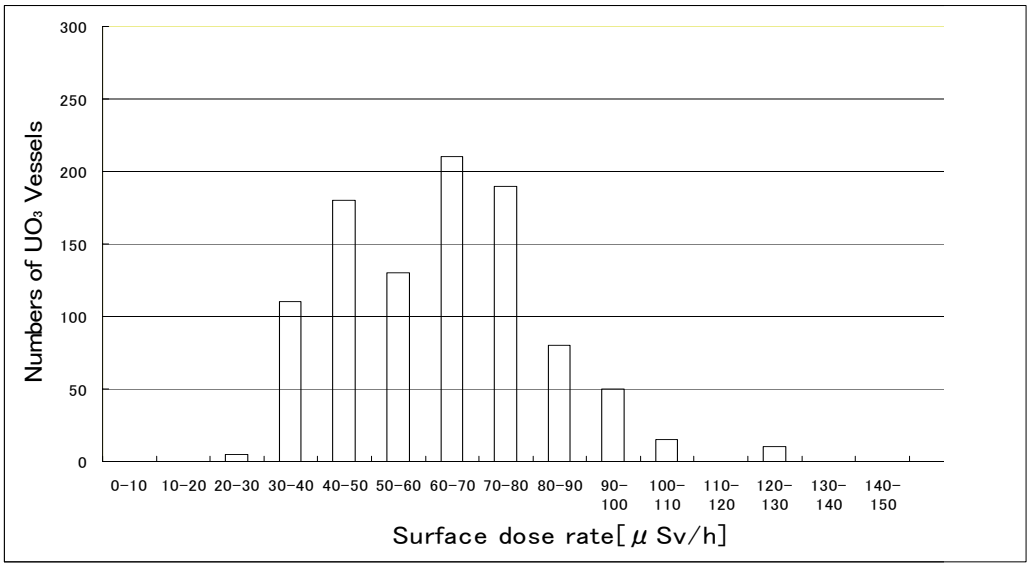

FIG. 4. The measurement results of the radiation dose rates on the UO_3 vessel surface.

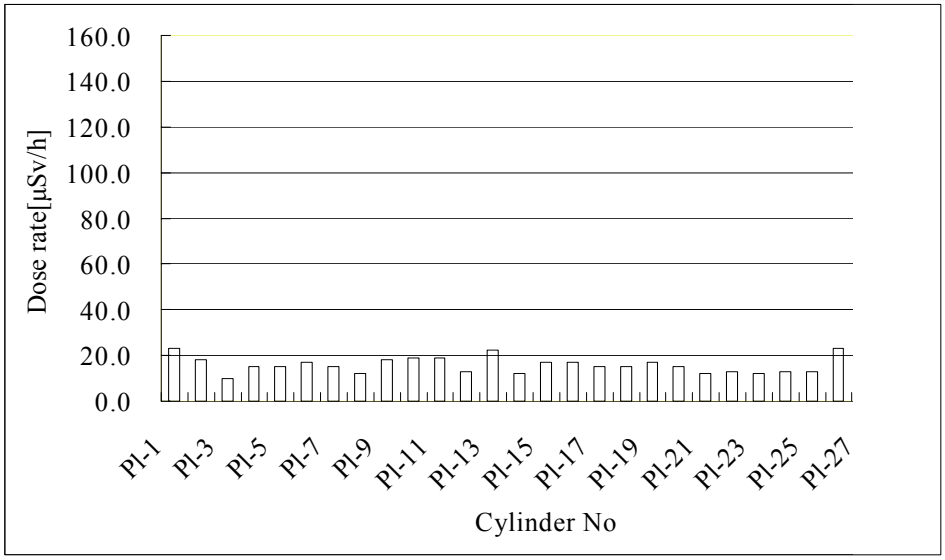

FIG. 5. The measurement results of the dose rate on the UF_6 cylinder surface.

3. Conclusion

Testing achievements on the conversion technology using RepU from the Tokai reprocessing plant are obtained. The construction of a future commercial RepU conversion facility will proceed on the results of the consistent research on and development of the RepU conversion technology, particularly on the establishment of the UO_3 hydration process and the operating conditions, on the solution of the radioactive nuclides behaviour and on the obtained corrosion data.

Furthermore, the centrifuge technologies have shown successful performance with different feed concentrations of RepU. This technique is quite difficult to operate because the separating work units (SWU) need to be well controlled.

ACKNOWLEDGEMENT

JAEA is pleased to make clear ideas for the RepU conversion technology through the consistent experiments made in collaboration with Japan's ten domestic electric companies and Japan Nuclear Fuel Limited (JNFL).

UTILITY EXPERIENCE AND POTENTIAL USE

(Session 5)

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India

Reprocessed uranium: 5 years operational experience in the Gundremmingen B BWR

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Abstract. Starting in the year 2002, RWE has inserted 316 fuel assemblies (FA) with reprocessed uranium (RepU) into the Gundremmingen B Boiling Water Reactor (BWR) core up to now. These fuel assemblies are of the AREVA ATRIUM 10x10 type and have been manufactured by Mashinostroitelny Zavod (MSZ) at Elektrostal near Moscow (Russia). The presentation of the operational experience of RepU within a mixed BWR core consisting of enriched natural uranium (ENU) FA, enriched reprocessed uranium (ERU) FA and MOX FA covers licensing issues, core management, core tracking (comparison of calculations and measurements), theoretical and practical influence of reactivity loss due to ^{236}U, and mechanical behaviour. The overall operational experience with RepU in the Gundremmingen B is as good as the one with 'normal' uranium FA.

1. Introduction

RWE Power AG in Germany is operating the 5 Nuclear Power Plant (NPP) units Biblis A and Biblis B, Emsland, Gundremmingen B and Gundremmingen C (see Table 1). Starting in the year 2002, RWE has inserted 280 fuel assemblies (FA) with reprocessed uranium (RepU) into the core of the BWR Gundremmingen B up to now.

The presentation of the operational experience of RepU within a mixed BWR core consisting of enriched natural uranium (ENU) FA, enriched reprocessed uranium (ERU) FA and MOX FA licensing issues, fuel handling and core management, core tracking, mechanical behaviour and economical influence of reactivity loss.

TABLE 1. NPP UNITS OPERATED BY RWE POWER AG

Unit	**PWR**			**BWR**	
	Biblis		**Emsland**	**Gundremmingen**	
	A	**B**		**B**	**C**
MWe	1204	1300	1310	1344	1344
No. of FA			193	784	784
Type of FA	16 × 16	16 × 16	18 × 18	10 × 10	10 × 10
Power density (kW/kg)	34.7	36.7	37.1	28.3	28.3

2. Fuel manufacturing and evolution of core composition

These FA are of the AREVA ATRIUM 10 × 10 type and have been manufactured by MSZ at Elektrostal (Russia). Up to now, 316 BWR ERU FA from MSZ have been delivered to the BWR Gundremmingen B. The only difference to the manufacturing of 'normal' Uranium AREVA fuel (manufactured at Lingen) lies within the UF_6 to UO_2 conversion process (Fig. 1).

Figure 2 shows the development of the Gundremmingen B core composition starting from a mainly 8 × 8 ENU core in 1984 via a 9 × 9 ENU core up to a mixed 10 × 10 ENU, ERU and uranium-plutonium mixed oxide (MOX) core in 2007.

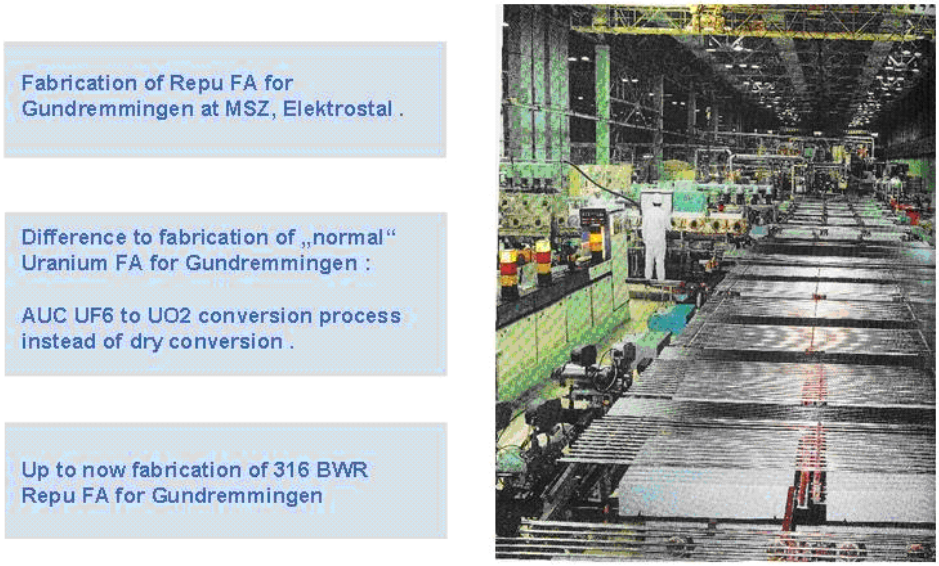


FIG. 1. Fabrication of ERU FA for the BWR Gundremmingen B.

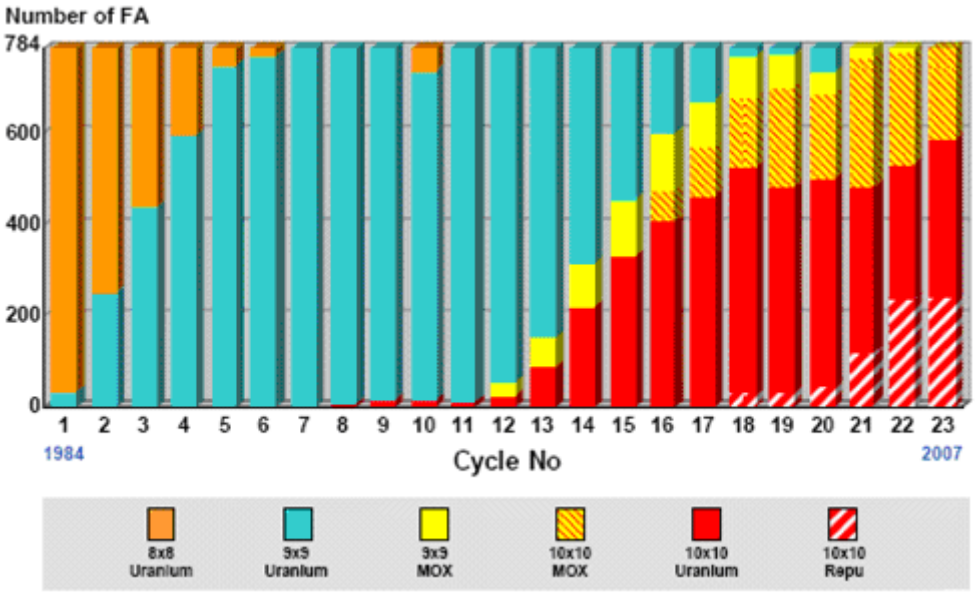


FIG. 2. Development of the core composition of the BWR Gundremmingen B.

3. Licensing of ERU fuel

From the beginning RWE Power's intention for the operation of ERU FA was to blend RepU with highly enriched ^{235}U to avoid economically unfavourable high ^{236}U contents. During the licensing procedure for such ERU FA for Gundremmingen B, all aspects of operation with ERU fuel have been investigated and proven to be of no safety issue (Table 2).

For instance, the activity inventory of the radiologically most relevant nuclides does not change by switching from 'normal' ENU fuel to ERU fuel (Table 3).

TABLE 2. LICENSING OF ERU FUEL OPERATION IN GUNDREMMINGEN B

- **Within the licensing procedure for fuel assemblies with ^{235}U enrichment up to 4.6 w/o for Gundremmingen B all aspects of ERU FA operation have been investigated and proven to be of no safety issue**

• Void coefficient	+5 %: No stability issue and within variations of +/– 20% for transient analysis
• Hot-cold swing	+0.06: No problem and overruled by reactivity loss
• Storage criticality	Less than 'normal' ENU FA
• Decay heat	Little higher than 'normal' ENU FA (Pu-238), but much less than MOX FA
• Activity inventory	Practically no change

- **The 9th 'Änderungsgenehmigung' (license) from 24 March 2000 according to § 7 of the German Atomic Energy Act included the operation of ERU fuel in Gundremmingen B**

TABLE 3. ACTIVITY INVENTORY OF RADIOLOGICALLY MOST RELEVANT NUCLIDES IN THE FA OF GUNDREMMINGEN B

Nuclide	Enriched Natural Uranium (ENU) 4.6 w/o ^{235}U (Bq/FA)	Enriched Reprocessed Uranium (ERU) 4.6 w/o ^{235}U (Bq/FA)
^{137}Cs	1.29 E15	1.20 E15
^{131}I	4.02 E15	4.02 E15
^{133}Xe	9.53 E15	9.53 E15
^{135}Xe	2.59 E15	2.56 E15

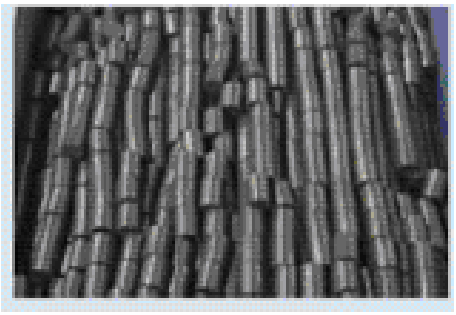
Burnup : 60 MWd/kg HM ; Decay time : 0

Finally, the 9th 'Änderungsgenehmigung' (license) from 24 March 2000 included the operation of ERU FA in the Gundremmingen NPP units within the limits given in Fig. 3.

4. Handling and storage procedures

Handling and storage procedures for ERU FA are the same as for 'normal' ENU FA (Fig. 4).

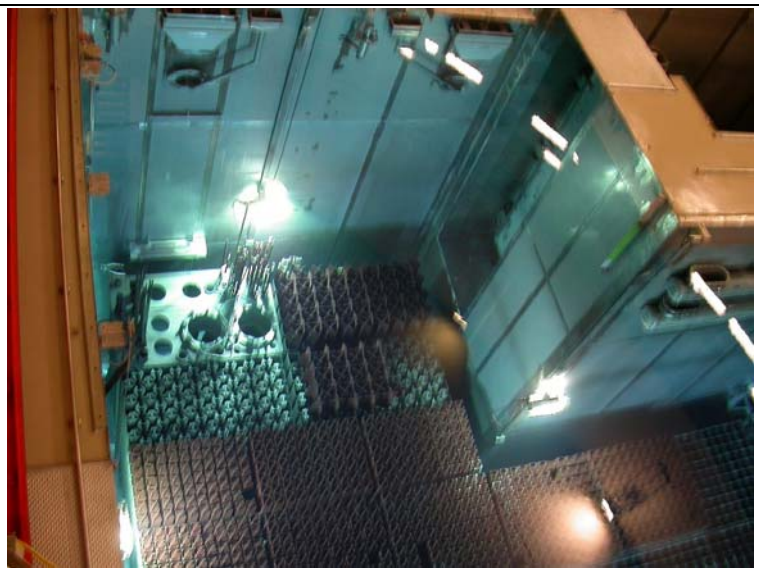
$^{232}U \leq 5 \times 10^{-7}$ w/o in U
$^{234}U \leq 0.10$ w/o in U
$^{236}U \leq 0.84$ w/o in U



Staying within limits not possible by direct physical enrichment of RepU

Blending of RepU with higher enriched uranium

FIG. 3. Today's ERU licensing limits of Gundremmingen NPP.



On plant site there is no difference in handling and storage and radiation protection between ERU fuel and ENU fuel.

Nothing special for enriched reprocessed uranium (ERU) fuel

FIG. 4. Gundremmingen B ERU fuel assembly handling and storage.

5. Core management and mechanical behaviour of ERU fuel assemblies

Although the enrichment distribution within the ERU FA is the same as within the 'normal' ENU FA the ERU FA are handled in the core management with an own nuclear database because of the ^{236}U content. Within a distinct bandwidth of the ^{236}U content the nuclear database need not be changed (Table 4 and Fig. 5). This bandwidth corresponds to a variation in reactivity that corresponds to an ^{235}U enrichment variation of about +/- 0.05 w/o.

As shown in Fig. 6, the overall accuracy of core tracking is not influenced by ERU FA.

TABLE 4. GUNDREMMINGEN B ERU FUEL CORE MANAGEMENT

1. ERU fuel is described with an own nuclear database.

2. All fuel assemblies with a ^{236}U content within the bandwidth

$$^{236}U \text{ w/o} = \times \text{ +/- } 0.15 \text{ w/o}$$

may be described with the same database as the fuel with × w/o ^{236}U.

+/- 0.15 w/o ^{236}U corresponds to +/- Δ k = 0.003, and

corresponds to +/- Δ a = 0.05 w/o ^{235}U

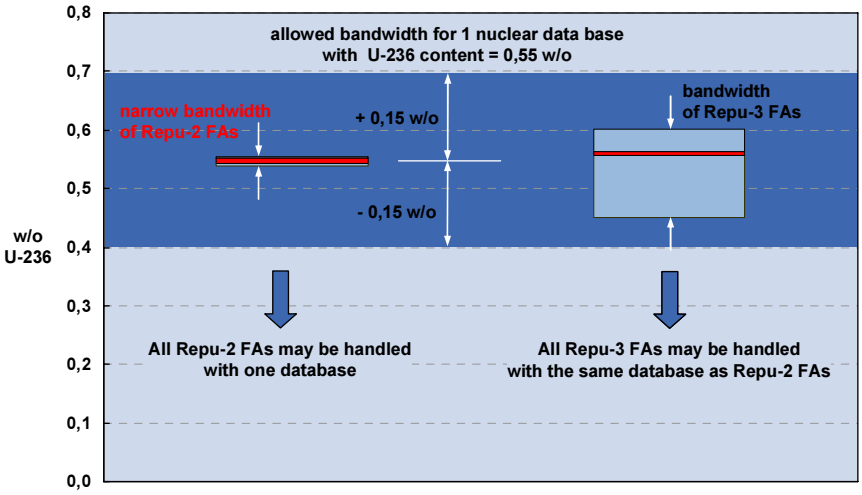


FIG. 5. Bandwidth of ^{236}U content in ERU FA for Gundremmingen B (Gundremmingen B ERU Core Management).

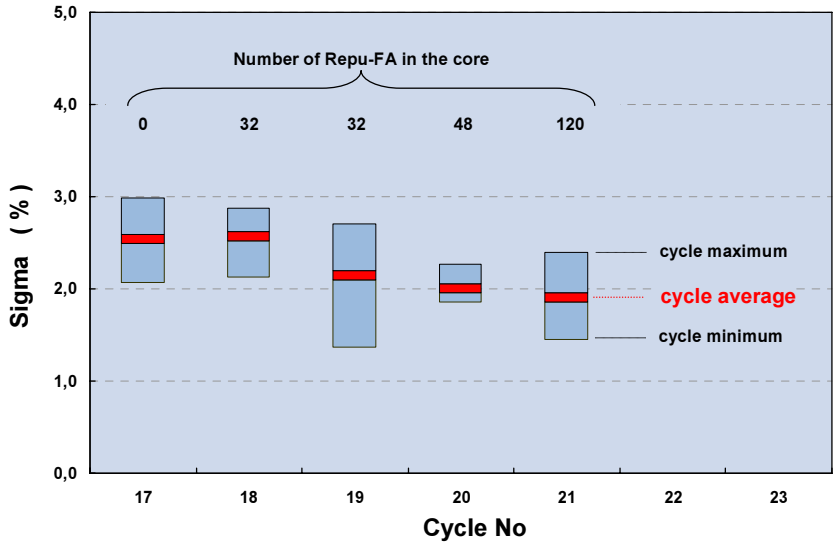


FIG. 6. Standard deviation TIP measurement against calculation in Gundremmingen B core tracking (overall accuracy).

A detailed investigation of local core tracking data seemed to show a power overestimation of ERU FA (see TIP cell 40 with 3 ERU FA in Fig. 7). However, an overview of the comparisons of measurement with calculation of cell 40 along the last cycles shows no influence of the ERU FA on local effects (Fig. 8). The local accuracy of core tracking is as independent of ERU FA as the overall accuracy.

Although there have been failed ERU FA in Gundremmingen B there are no hints for failure characteristics which are typical for ERU FA (Fig. 9).

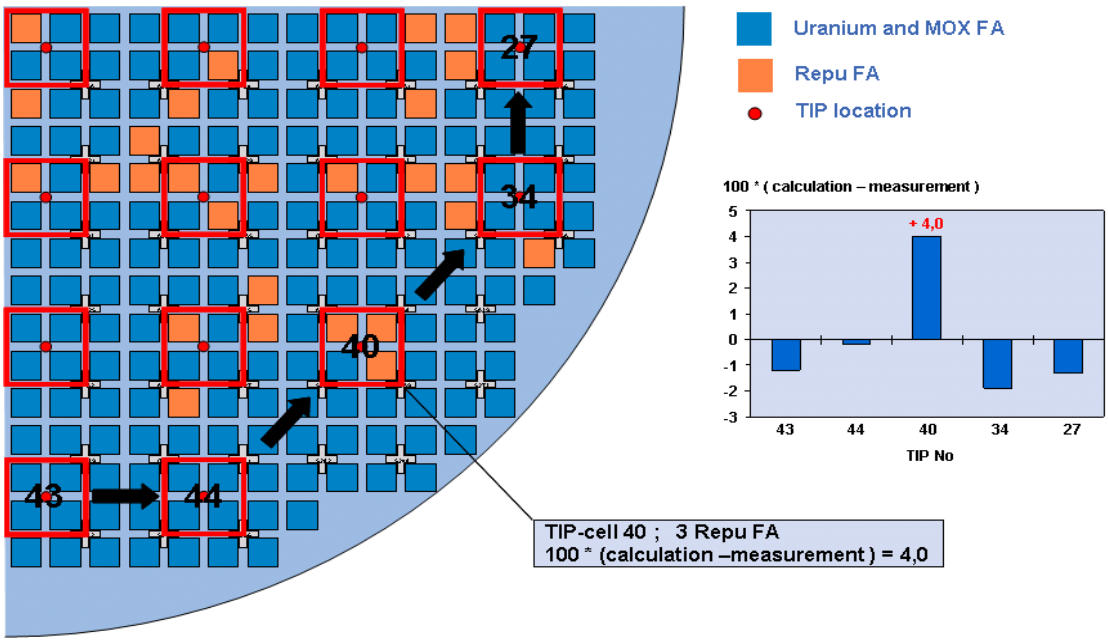


FIG. 7. Gundremmingen B core tracking (cycle 21, ¼-core, local deviation in TIP cell 40).

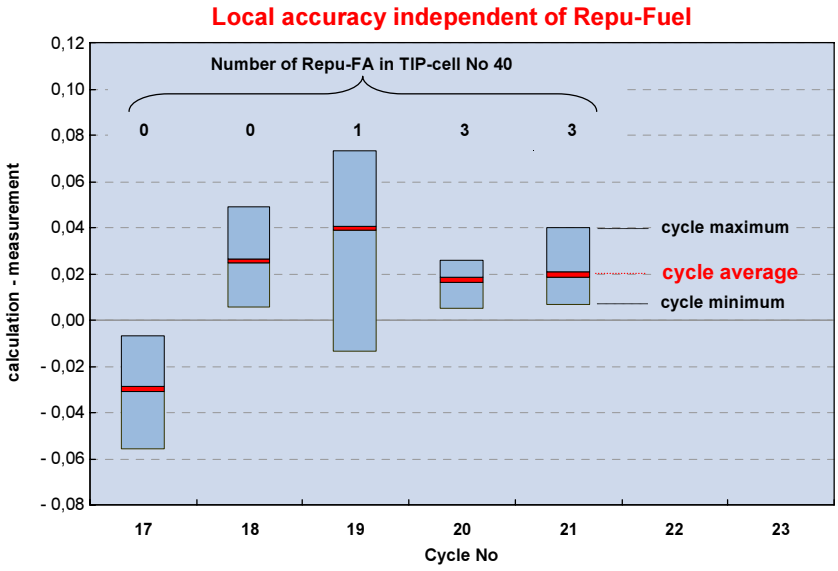
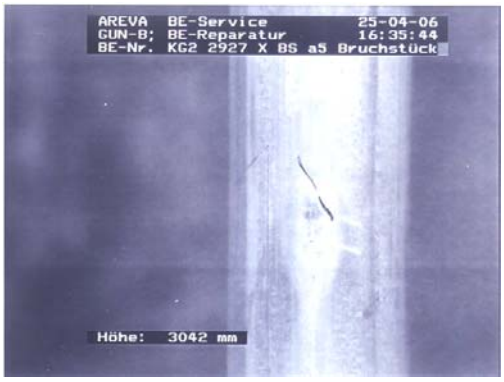


FIG. 8. Deviation of TIP cell 40: Measurement against calculation in Gundremmingen B core tracking (local accuracy of 'problematic ?' TIP cell 40).



One	RepU fuel rod failure caused by debris in autumn 2005
Three	RepU fuel assemblies failed on symmetric core positions in spring 2007 Cause is under investigation. Suspect : Power history

FIG. 9. Mechanical behaviour of ERU FA in Gundremmingen B.

6. Reactivity losses due to ^{236}U

The reactivity loss caused by the neutron absorber ^{236}U in ERU FA results typically in $\Delta k \approx 0.011$ for the FA in Gundremmingen B (Fig. 10). This reactivity loss could be compensated by an additional enrichment of ~ 0.16 w/o ^{235}U, this being at the lower edge of the expected bandwidth (Fig. 11).

Because most fuel rods in the Gundremmingen FA have enrichments of 4.95 w/o ^{235}U, a further enrichment for the compensation of ^{236}U is not possible without violating the 5.00 w/o ^{235}U limit. Moreover, a ^{236}U compensation is not included in the license. Therefore, the operation of ERU FA in Gundremmingen B results in a typically 3.5 % higher ERU FA consumption compared to 'normal' ENU FA (Table 5).

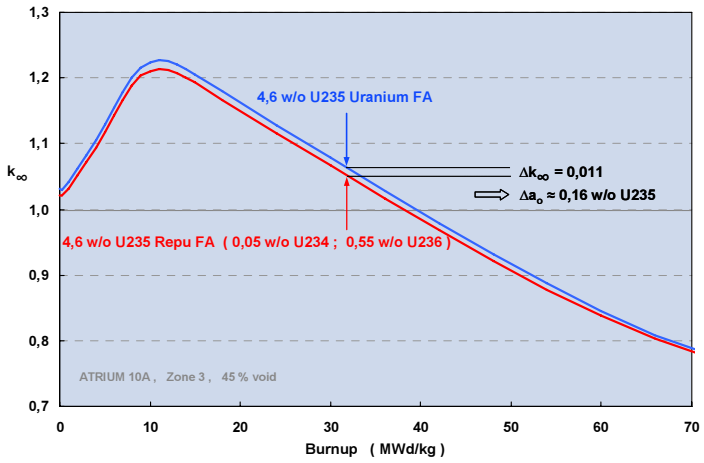


FIG. 10. Typical k_∞ developments of ENU and ERU FA for the BWR Gundremmingen B.

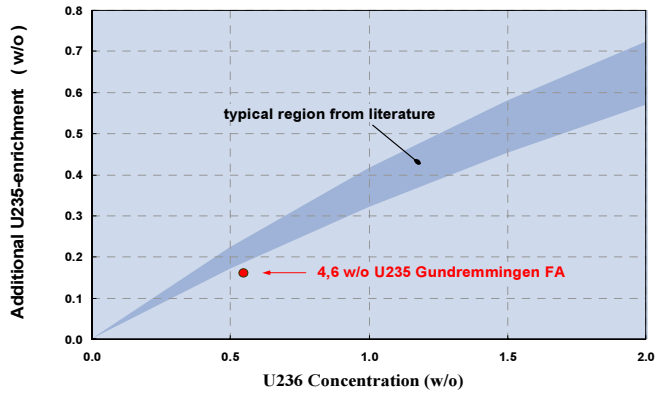


FIG. 11. Possible compensation of ^{236}U by additional enrichment of ^{235}U.

TABLE 5. IMPACT ON THE FUEL CYCLE ECONOMICS OF GUNDREMMINGEN B

Most fuel rods in the FA of Gundremmingen B have enrichments of 4.95 w/o ^{235}U

↓

Compensation of ^{236}U by higher ^{235}U enrichment is not possible
(and is also not included in the license)

↓

ENU and ERU FA in Gundremmingen B have the same ^{235}U enrichment distribution

↓

ERU FA have a reactivity lack against ENU FA

↓

Typically 3.5 % higher FA consumption with ERU FA

7. Conclusion

The overall operational experience with ERU FA in the Gundremmingen B BWR is as good as the one with ‘normal’ ENU FA.

The use of reprocessed uranium in light water reactors: Problem identification and solution finding

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Abstract. Of the three main options available to the utility Energie Baden-Wuerttemberg (EnBW) for the use of reprocessed uranium (RepU) to produce enriched uranium for the manufacturing of nuclear fuel assemblies (FA) two have been used: the re-enrichment by centrifuges and blending with high-enriched uranium. The decision was influenced by commercial and technical conditions. Following the reasons also mentioned in Chapter 4.1.2.5 of IAEA-TECDOC-1529 [1] the use of RepU as matrix for (mixed oxide) MOX FA was not considered, the main argument being the intention to use as much as possible plutonium per FA due to the high MOX fabrication costs compared with Unat or enriched reprocessed uranium (ERU[a]) fuel fabrication. The isotopic composition of natural uranium (Unat) and RepU, the description of the corresponding isotopes as well as the various recycling possibilities are detailed extensively in the document IAEA-TECDOC-1529 of February 2007.

1. History

This section shows the process of decision making and describes early practical RepU fuel experience with the example of EnBW. EnBW's policy was **not** to use RepU as strategic inventory but to recycle reprocessing products as soon as possible.

The licensing conditions concerning the use of RepU for German reactors vary. There are plants with operating licences containing limits such as maximum permissible initial enrichment or maximum values for ^{236}U in the fuel as well as relatively open licences concerning quantity of assemblies and grade of enrichment allowing utilities to decide about the insertion of ERU fuel into the reactor core. Besides the reactor in Obrigheim (Kernkraftwerk Obrigheim (KWO); PWR; 357 MW(e)) EnBW dedicated two PWR reactors in Neckarwestheim (Neckarwestheim I and II; 840 and 1400 MW(e), respectively) to RepU recycling. According to the operating licences of these plants it is necessary to prove to the authority before delivery of the fuel that the ERU enrichment is equivalent to the licensed maximum enrichment with Unat.

The legal background at the time when the first decision concerning RepU recycling arose in the 1990s was different from today's situation. Before 1994, the German utilities were obliged to conclude reprocessing contracts for their spent fuel. Evidence of existing contracts had to be provided for the quantities of fuel to be discharged in six consecutive years. After 1994, the utilities could decide about their way of 'Entsorgung': there was the alternative either to choose reprocessing and recycling or long-term intermediate storage and direct final disposal. Until the most recent amendment of the German Atomic Energy Act in 2002 the option to go for reprocessing later was also available.

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[a] The abbreviation 'ERU' is introduced to be able to distinguish between RepU = direct product of reprocessing with an ^{235}U content corresponding to that of the spent fuel and ERU = RepU after re-enrichment to the ^{235}U content necessary for fuel fabrication.

For criticality reasons a limit of 5 wt% ^{235}U in the material to be processed or transported had generally been applied for facilities in the nuclear fuel cycle (enrichment facilities, fuel fabrication plants, etc). It had also been the maximum in the licences for transport means such as cylinders for UF_6, flasks for unirradiated FA, etc. This value may have to be adapted in the future.

2. Enrichment by centrifuges

When COGEMA's UP2 plant in La Hague (France) had been adapted to reprocess uranium oxide fuel, German utilities started a RepU recycling project with 110 ERU fuel rods in one fuel assembly (FA) in the Obrigheim PWR at the beginning of the 1980s (total fuel rods per FA: 180). The enrichment of the ERU rods was 3.5 wt% ^{235}U absolute, equivalent to 3.2 wt% ^{235}U in Unat. The ^{235}U content was increased as compensation of the ^{236}U content in the RepU. The fuel assembly was loaded into the reactor in 1983 and finally discharged in 1986 after three reactor cycles. It was later reprocessed in the WAK pilot reprocessing plant in Karlsruhe (Germany). After each cycle ERU fuel rods were removed for hot-cell examinations in the Karlsruhe institutes. The operational experience was exactly the same as with Unat FA in the core at the same time.

Around 1980, the average discharge burnup was in the range of 32 GW•d/t HM. Table 1 indicate that there was enough safety margins to the 5 wt% ^{235}U limit for centrifuge-enriched ERU. Only ERU produced from spent fuel with a burnup of 52 GW•d/t HM would have exceeded that value.

Till the mid-1980s, the average burnup moved to 37 GW•d/t HM, i. e. the spent fuel quality was still suitable for centrifuge enrichment of the RepU.

The second German ERU project consisted of two manufacturing campaigns with four ERU FA each for the Neckarwestheim I PWR, loaded into the reactor in 1986 and 1987.

TABLE 1. CALCULATION OF ^{236}U COMPENSATION FOR FUEL IN THE 2nd GENERATION WITH 3.5wt% ^{235}U

ERU from fuel with a burn-up of	**Before re-enrichment**			**After re-enrichment**		**Factors**	
	1st generation			**2nd generation equiv.to**		**Feed**	**SWU**
GW•d/t HM	U-235	U-235	U-236	U-235	U-235	tails assay 0,25%	U-235
32	3.50%	1.02%	0.43%	3.86%	3.50%	4.69	3.93
36	3.50%	0.84%	0.45%	3.97%	3.50%	6.31	4.97
40	3.50%	0.69%	0.47%	4.12%	3.50%	8.80	6.24
44	3.50%	0.56%	0.48%	4.33%	3.50%	13.16	7.89
48	3.50%	0.45%	0.49%	4.62%	3.50%	21.80	10.08
52	3.50%	0.36%	0.50%	5.05%	3.50%	43.64	13.10
Enrichment of natural uranium 0.711				**:**	3.50%	7.05	4.81

The spent fuel for these projects was reprocessed in COGEMA's UP2 plant in La Hague in 1984 and in the WAK plant in Karlsruhe. The process product was uranyl nitrate hexahydrate (UNH) which was converted into UF_6 in the COMURHEX facilities at Pierrelatte (France). The RepU was delivered to URENCO in August 1985 and July 1986; enrichment took place in URENCO's Almelo (The Netherlands) plant. Immediately thereafter the fuel was fabricated in Hanau (Germany). The absolute enrichment was 3.72 and 3.76 wt% ^{235}U, corresponding to an equivalent Unat enrichment of 3.5 wt%

^{235}U. The operating experience was comparable to Unat fuel.

Although the uranium hexafluoride (UF_6) was enriched without considerable delay after reprocessing and conversion into UF_6, the feed RepU of the second campaign had to be diluted with Unat due to the ^{232}U content exceeding the licensing limits of the enrichment plant at that time.

Four of these fuel assemblies were finally discharged in 1990 with a burnup of 39 GW•d/t HM and delivered to COGEMA's La Hague facilities in 1992. No additional documentation was necessary for transport and handling of the fuel after irradiation. Reprocessing took place in November 2006. No detailed information about the isotopic composition of the RepU is available. The small quantity was diluted with other fuel.

Four FA, finally discharged in 1992 (burnup: 42 GW•d/t HM) were loaded into a CASTOR cask in 2001 and are currently in the on-site interim storage facility.

For loading of ERU fuel into dry storage casks additional licensing actions are required. An additional licensing procedure for the casks has to be started. The registration certificate (Zulassungsschein) of the casks has to be modified (Inventarerweiterung) and the licence of the storage facility has also to be adapted.

Before the next RepU deliveries were imminent the initial enrichment limits for Unat FA in EnBW's reactors had been raised to 4.0 wt% ^{235}U in a first step (and later to 4.4 wt% ^{235}U in a second step). The further development and advancement of the basic FA structural materials (to reduce oxide layers, etc.) allowed longer operating times and considerably higher burnups. A precondition was to increase initial enrichment grades.

TABLE 2. CALCULATION OF ^{236}U COMPENSATION FOR FUEL IN THE 2nd GENERATION WITH 4.0 wt% ^{235}U

ERU from fuel with a burn-up of		**Before re-enrichment**		**After re-enrichment**		**Factors**	
		1st generation		**2nd generation equiv.to**		**Feed**	**SWU**
GW•d/t HM	**U-235**	**U-235**	**U-236**	**U-235**	**U-235**	tails assay 0,25%	U-235
32	3.50%	1.02%	0.43%	4.41%	4.00%	5.40	4.83
36	3.50%	0.84%	0.45%	4.54%	4.00%	7.27	6.03
40	3.50%	0.69%	0.47%	4.71%	4.00%	10.14	7.49
44	3.50%	0.56%	0.48%	4.95%	4.00%	15.16	9.40
48	3.50%	0.45%	0.49%	5.28%	4.00%	25.09	11.92
52	3.50%	0.36%	0.50%	5.77%	4.00%	50.18	15.40
Enrichment of natural uranium 0.711					4.00%	8.13	5.83

In this transition period to higher initial enrichment the RepU came from spent fuel with an initial enrichment of about 3.5 wt% ^{235}U. The new fuel to be manufactured, however, required an enrichment grade with a reactivity equivalent to 4.0 wt% ^{235}U Unat. Table 2 shows that this was only possible by centrifuge enrichment without exceeding 5.0 wt% ^{235}U if the burnup of the spent fuel of the first generation was around 44 GW•d/t HM. The average discharge burnup of the EnBW reactors was above 40 GW•d/t HM for the first time in 1989.

3. Enrichment by blending

Towards the end of the 1990s, the average burnup went up to the high forties (close to 50 GW•d/t HM). Therefore, the beginning of the cooperation between Siemens (today AREVA NP) and OAO Mashinostroitelny Zavod (MSZ) in Elektrostal near Moscow (Russia) in 1994 brought a solution for material with such properties. MSZ offered to blend RepU with higher enriched uranium from inventories which were not required for other purposes. The evaluations that were made at that time are today no longer interesting, because the market conditions have changed completely. It can, however, be said that the commercial conditions for blended ERU fuel at that time were comparable to fuel produced using Unat.

Table 3 shows that with an initial enrichment in the new fuel of the 2nd generation of 4.4 wt% ^{235}U and the necessary ^{236}U compensation, centrifuge enrichment is no longer appropriate for technical reasons. In that case the 5 wt% limit is already exceeded with a burnup of 40 GW•d/t HM in the spent fuel.

A look at the feed factors in Table 3 makes clear that - even if enrichment including ^{236}U compensation could be realized - a negative cost effect occurs due to the high conversion costs of RepU into UF_6 and the high SWU component. With an average discharge burnup of 52 GW•d/t HM the feed factor is six times higher than for Unat and the SWU factor is nearly tripled. Thus, an economic benefit in favour of the blending path becomes obvious.

Accordingly, the offer to blend RepU was accepted and lead test rods and test assemblies, in the first campaigns fabricated with Unat, were introduced into the KWO reactor from 1995 to 1997. A total of 48 ERU FA were fabricated for KWO with an enrichment of 4.1 wt% ^{235}U, equivalent to 3.95 wt% ^{235}U Unat.

TABLE 3. CALCULATION OF ^{236}U COMPENSATION FOR FUEL IN THE 2nd GENERATION WITH 4.4wt% ^{235}U

ERU from fuel with a burn-up of		**Before re-enrichment**		**After re-enrichment**		**Factors**	
		1st generation		**2nd generation equiv. to**		**Feed**	**SWU**
GW•d/t HM	**U-235**	**U-235**	**U-236**	**U-235**	**U-235**	tails assay 0.25%	U-235
32	3.50%	1.02%	0.43%	4.85%	4.40%	5.97	5.554
36	3.50%	0.84%	0.45%	5.00%	4.40%	8.05	6.90
40	3.50%	0.69%	0.47%	5.18%	4.40%	11.21	8.51
44	3.50%	0.56%	0.48%	5.45%	4.40%	16.74	10.61
48	3.50%	0.45%	0.49%	5.80%	4.40%	27.73	13.41
52	3.50%	0.36%	0.50%	6.35%	4.40%	55.46	17.26
Enrichment of natural uranium 0.711				**:**	**4.40%**	**9.00**	**6.66**

At the end of 1997, EnBW signed another contract for the delivery of 56 ERU FA until 2001 for the Neckarwestheim II NPP. The first fabrication campaign of 28 FA had an enrichment of 4.35 wt% ^{235}U, equivalent to 4.2 wt% ^{235}U Unat. The second campaign was enriched to 4.6 wt% ^{235}U, equivalent to 4.4 wt% ^{235}U Unat. Design and structural material of the FA corresponded to that of the simultaneously loaded Unat FA.

The enrichment of the first campaign of 4.35 wt% ^{235}U was chosen because at the time of fuel delivery no transport containers for higher ^{235}U contents were available.

Operational experience gained until now with blended ERU fuel can also be compared to Unat fuel. There is a small penalty in form of a 0.5 to 0.75 % loss of reactivity. This loss was calculated with two virtual equilibrium cycles. An abstract reload of 44 Unat FA with an enrichment of 4.4 wt% ^{235}U was compared with 44 ERU FA enriched to 4.68 wt% ^{235}U by blending. The enrichment grade of these virtual ERU FA was defined conservatively using the worst possible (limits of operating licence) RepU quality.

Experience has shown some inconveniences in connection with the blending process which are not too significant, but at least may mean additional activities and expenses:

- The blending process is currently only offered in Russia. Safeguards agreements, however, do only with additional requirements or even not at all allow nuclear material with certain codes to be transported into Russia (Codes A, C, etc). That means that obligations swaps may be necessary to enable a transfer of RepU into Russia. All licensing activities are usually provided by the fuel fabricator and do not lead to extra efforts by the utility, but may mean additional lead time.
- Necessary actions of utility personnel inter alia in connection with on-site quality assurance during the fabrication process require more time, effort and expenses due to the great distance.
- If ERU FAs are fabricated completely in Russia, this means that for delivery of a complete reload quantity many transport containers are combined in one single transport. A larger quantity of FA as usual will arrive at the reactor site at the same time requiring intermediate storage and making on-site handling more complicated. The transport route for assemblies from Russia via ship requires good planning to avoid interference with bad weather conditions, especially in winter time.

4. Costs

Cost comparisons made in the past were based on low prices for uranium. But the market has changed and uranium prices are very high today. The replacement of Unat fuel by ERU fuel may nevertheless be worthwhile despite the required over-enrichment for ^{236}U compensation, because reprocessing costs are allocated to the spent fuel and RepU is available practically free of charge.

Figures 1 and 2 have been calculated using different prices for uranium concentrate (40, 100, 140 US$/lb U3O8). The price (or cost) for the conversion and enrichment of Unat was based on the TradeTech's long-term value for Europe for June 2007. For fuel fabrication a value was inserted which is applied for general calculations by VGB in Germany.

For centrifuge-enriched ERU fuel it was assumed that conversion costs of RepU are about six times higher than Unat conversion and that there is a penalty for enrichment of RepU. It was further assumed that RepU is converted directly into UF6. The costs for ERU fuel produced by blending are assumed to be in the same range as Unat fuel.

The first example (see Fig. 1) is related to an enrichment of 4.0 *wt%* in the 2nd generation fuel, the initial enrichment of the first generation fuel was 3.5 *wt%* ^{235}U. If the enrichment of the 2nd generation is increased to 4.4 *wt%* ^{235}U (see Fig. 2), there are cases where centrifuge enrichment is possible according to commercial conditions.

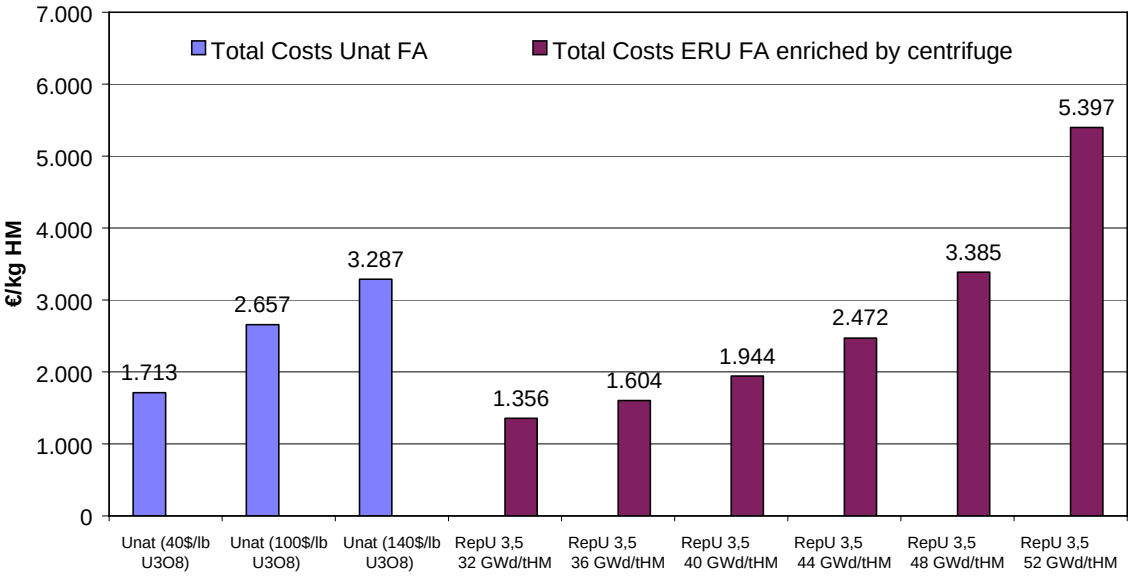

FIG. 1. Costs of Unat FA enriched to 4.0 wt% ^{235}U with different U_3O_8 prices and of ERU FA with RepU from spent fuel with 3.5 wt% ^{235}U and different burnups enriched to the equivalent of 4.0 wt% ^{235}U with a tails assay of 0.25 wt% ^{235}U.

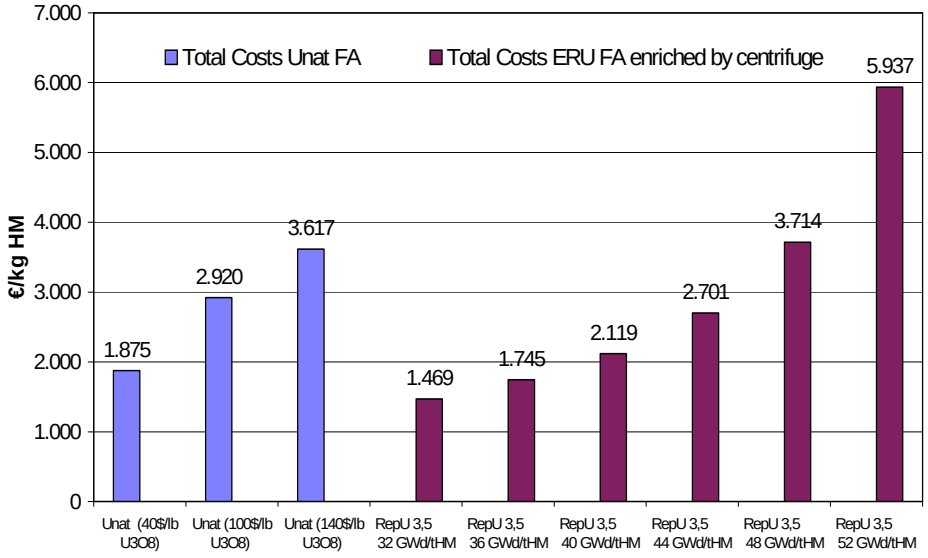

FIG. 2. Costs of Unat FA enriched to 4.4 wt% ^{235}U with different U_3O_8 prices and of ERU FA with RepU from spent fuel with 3.5 wt% ^{235}U and different burnups enriched to the equivalent of 4.4 wt% ^{235}U ^{235}U with a tails assay of 0.25 wt% ^{235}U.

5. Conclusion

Experience has proven the practicability of both alternatives, centrifuge enrichment and blending, without major difficulties. Material properties, technical parameters, licencing limits, etc. have to be considered early and carefully. The commercial aspects of uranium and fuel markets together with the question of further recycling in 3rd generation fuel will influence the final decision.

The facts stated in this paper make clear that it is implicitly necessary to identify for each individual reactor as early as possible technical and legal limits and hurdles, to clarify which possibilities may be realized to assure that a further use of the material in the next generation is possible and reasonable.

The improvement of basic structural materials mentioned earlier and the consequential higher burnups reduce the residual content of ^{235}U and increase ^{236}U in the RepU, i. e. lead to inferior RepU quality. This, in turn, requires higher enrichment components for both blending and centrifuge options. It may even render the centrifuge option impossible. In addition, the use of blending to create ERU kills two birds with one stone. It helps to solve the problems in connection with increased ^{232}U, ^{234}U, and ^{236}U content and it helps to destroy or at least diminish high enriched material inventories that could be hazardous. The situation might change again with the further development of laser enrichment technologies.

TABLE 4. ISOTOPIC COMPOSITION OF VARIOUS URANIUM FUELS WITH AN INITIAL ENRICHMENT OF 4.0 W/0 ^{235}U OR AN ENRICHMENT EQUIVALENT TO 4.0 W/0 ^{235}U, WITH A BURNUP OF 51 GW•d/t HM, RESPECTIVELY

Assumed conditions for insertion in GKN II: 3.850 MW th; 340 EFPD* × 4; 535 kg HM/FA, 37.3 kW/kg						
1st generation fuel			**2nd generation fuel**		**2nd generation fuel**	
Isotop	U-Fuel 4 w/o (ex U-nat)		ERU-Fuel 4.16 w/o (ex URe+blending)		ERU-Fuel 4.59 w/o (ex Ure+centrifuge)	
	Discharge w/o (U-tot)	Storage: 5a w/o (U-tot)	Discharge w/o (U-tot)	Storage: 5a w/o (U-tot)	Discharge w/o (U-tot)	Storage: 5a w/o (U-tot)
U-232	1.270 E-7%	2.997 E-7	4.707 E-7	7.014 E-7	7.711 E-7	1.272 E-6
U-234	0.021	0.023	0.29	0.031	0.086	0.090
U-235	0.643	0.643	0.774	0.774	0.978	0.978
U-236	0.576	0.577	1.056	1.056	2.301	2.301
U-238	98.760	98.758	98.141	98.139	96.635	96.631
U-tot (g/kg)	934.993	935.010	933.862	933.883	932.584	932.622
w/o (Pu-tot)	w/o (Pu-tot)	w/o (Pu-tot)	w/o (Pu-tot)	w/o (Pu-tot)	w/o (Pu-tot)	
Pu-238	3.043	3.236	3.866	4.046	7.789	7.904
Pu-239	49.261	51.183	50.635	52.600	49.622	51.517
Pu-240	24.600	25.248	23.051	23.686	22.089	22.685
Pu-241	14.880	11.937	15.016	12.068	14.065	11.313
Pu-242	8.224	8.396	7.432	7.599	6.434	6.581
Pu-tot (g/kg)	11.297	11.066	12.047	11.783	12.214	11.942

* effective full power days

To safe costs, for utilities with options in reprocessing contracts an early decision is necessary about the form in which RepU will be returned. The expenses for conversion of uranyl nitrate into U_3O_8 (for blending) or UF_6 (for re-enrichment via centrifuges) as well as for subsequent storage of the converted product vary considerably.

Early action and consideration is also recommended if later reprocessing of the burnt ERU fuel is envisaged to create 3rd generation fuel. Since reprocessing means separation of uranium and plutonium, the recyclability of both products is required. A further important point is, therefore, to respect the limits of existing reprocessing and MOX fabrication plants. In the technical specification for projected facilities this should be considered - where feasible - to avoid problems in future.

Table 4 shows that reprocessing of discharged ERU fuel might lead to RepU qualities that are not easily processed further. Even if laser enrichment were available the question how to handle the arising depleted uranium (DU) remains.

The adaptations of licensing values for NPPs as well as for facilities of the various processing steps in the nuclear fuel cycle have to be launched in good time to guarantee undisturbed treatment of future RepU quantities. The same is valid for licensing procedures for all means of transport such as cylinders, containers and flasks for Unat, RepU, ERU as well as transport and storage casks for fresh and irradiated fuel.

It is obvious that a well-timed forward planning is absolutely necessary and a prerequisite for a successful RepU recycling strategy.

ACKNOWLEDGEMENTS

The author wish to thank Mr. Johann Staudinger (KWO), Dr. Hans-Georg Johann (GKN) and Dr. Wolf-Dieter Perschmann for their contributions.

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Necessary conditions for the development of reprocessed uranium recycling

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Abstract. Electricite de France (EDF) has gathered a strong experience in reprocessed uranium (RepU) recycling since the first enriched reprocessed uranium (ERU) fuel assembly was loaded in 1987 and considers the possibility of increasing the use of this recycled fuel. This paper describes the history and the lessons learned from experiments of RepU recycling and the difficulties foreseen and the technical and economic challenges to answer in order to allow RepU to play a more significant role in the nuclear fuel supply.

1. Operational experience of RepU recycling at EDF

1.1. History of RepU recycling in EDF reactors

EDF has studied the possibility of recycling RepU in Pressurized Water Reactors (PWR) in the early 1980s. Precursor fuel assemblies were loaded in the Cruas-4 NPP from 1987 to 1990 and a first ERU fuel reload was introduced in the same NPP in 1994. EDF, unlike other European utilities, has used pure ERU fuel directly enriched from its own RepU by the gas centrifuge technology, instead of enrichment by blending with previously enriched uranium. This method yields more restrictive conditions on reuse options due to higher concentrations of minor isotopes in the enriched product. At the time of the first ERU reload (1994) EDF had started a new core management for the Cruas PWRs using enriched natural uranium (ENU) fuel with an enrichment of 3.7% ^{235}U. It was decided to use ERU fuel with the same enrichment of 3.7% ^{235}U. As the negative effect of the isotopes ^{234}U and ^{236}U was not compensated by a higher enrichment of ^{235}U, this fuel was only equivalent to ENU fuel with an ^{235}U assay of 3.4%. Nine reloads of the same type were introduced alternately in Cruas-3 and Cruas-4 from 1994 to 1999.

A project aiming at enhancing the energy content of ERU fuel up to the equivalence with ENU fuel was developed since 1994:

- As a first step, the number of ERU subassemblies was increased (44 instead of 40). This allowed to get the same energy content as in an ENU reload, without changing the ^{235}U assay and with no impact on safety limits. However, this method increased also the ERU fuel cost by 10%.
- A license to load ERU fuel assemblies with a ^{235}U assay up to 4.1% was obtained in 1998. The safety studies showed that 4 additional control rod clusters were necessary to keep the reactivity margins at the same level as with ENU fuel. This modification was made for the Cruas-3 and Cruas-4 reactors and the first ERU fuel reload of this kind was introduced in 1999 (URE10 (see Table 1)).
- In the meantime, due to these difficulties and to lack of competitiveness of ERU fuel compared to ENU fuel at this time, no decision was made to increase the quantity of recycled RepU, and the average number of ERU reloads was kept between 1 and 2 reloads per year during the period 1995 to 2005 (see Table 1). RepU that is not recycled is securely stored as U_3O_8 in AREVA's facilities at Pierrelatte.

TABLE 1. HISTORY OF ERU FUEL LOADING IN THE CRUAS PWRs

ERU Reload	Year Loaded	Reactor	^{235}U Assay (%)	Number of Fuel Assemblies	Quantity of ERU Loaded (kgU)
	1987	Cruas-4	3.25	4	1846
	1987	Cruas-4	3.55	4	1847
URE1	1994	Cruas-4	3.70	24	11 038
	1995	Cruas-4	3.70	2	919
	1995	Cruas-4	3.70	6	2760
URE2	1995	Cruas-3	3.70	36	16 557
URE3	1996	Cruas-2	3.70	44	20 212
URE4	1996	Cruas-4	3.70	44	20 203
URE5	1997	Cruas-3	3.70	40	18 383
URE5	1997	Cruas-3	3.70	4	1840
URE6	1997	Cruas-4	3.70	36	16 536
URE7	1998	Cruas-3	3.70	36	16 517
URE8	1998	Cruas-4	3.70	44	20 240
URE9	1999	Cruas-3	3.70	44	20 191
URE10	1999	Cruas-4	3.95	40	18 346
URE11	2000	Cruas-3	3.95	36	16 541
URE12	2001	Cruas-4	3.95	40	18 380
URE13	2002	Cruas-3	3.95	36	16 550
URE14	2003	Cruas-4	3.95	40	18 372
URE15	2004	Cruas-3	3.95	40	18 334
URE16	2005	Cruas-3	3.95	40	18 399
URE17	2005	Cruas-4	3.95	40	18 400
URE18	2006	Cruas-4	4.00	40	18 400

1.2. Lessons learned from this experience

The impacts on operation, radioprotection and environment were as follows:

- The impact of reactor modifications due to the addition of 4 control rod clusters was found negligible. These modifications were made during maintenance outages and did not increase the length of these outages.
- There was no impact at all on the operation of the NPPs, neither during electricity production nor during outages.
- There was no impact on the waste (effluents and off-gas) released to the environment.
- The total annual radiation dose was supposed to increase by less than 0.1% due to the handling of ERU fuel assemblies before they were stored under water. Actually, this increase could not be detected by on-field measurements.

The impacts on overall performance and economy were as follows:

- The license to load ERU fuel assemblies with a ^{235}U assay up to 4.1% was obtained later than expected at the beginning of the project. Thus, bigger reloads (44 subassemblies instead of 40) had to be used longer than expected leading to unwanted extra fuel cost.
- Although the fuel was later authorized to be over-enriched, the complexity induced by the need to adjust the ^{235}U assay at each reload was difficult to manage and led to some inaccuracy of the enrichment on some reloads. In some cases, a few equivalent full power days (EFPD) (between 0.5 and 8) were lost compared to ENU fuel. This problem has been maximum for the last reload (URE18), which used RepU recently recovered directly at the output of the reprocessing plant,

whereas the previous reloads used RepU produced much earlier. This difference points out another issue that will be addressed in the next section: the evolution of RepU characteristics with reprocessed fuel burnup.

2. Future plans and limitations

The annual quantity of EDF's RepU coming out of the reprocessing plant is close to 850 tU/year, which means more uranium has been stored for future use than recycled at once. A few years ago, anticipating higher natural uranium prices in the future, EDF started looking at an increase of RepU recycling to the maximum possible of two reloads per year in Cruas-3 and -4.

However, for economic reasons and problems of compliance with new regulations, AREVA decided to close down its RepU conversion facility in 2008 and stopped the conversion operations from uranyl nitrate hexahydrate (UNH) to UF_6 as soon as 2006. As a consequence, there was only one reload in 2006, and there will be no ERU reload at Cruas in 2007.

In the meantime, EDF has concluded through TENEX an agreement for conversion and enrichment of RepU. It uses the facilities of the Siberian Group of Chemical Entreprises (Seversk, Russia). The feed material is U_3O_8 which has been converted from UNH in AREVA's TU5 facility at Pierrelatte (France). The first ERU will be delivered by TENEX in 2007 and will allow to resume ERU fuel loading in Cruas in 2008. EDF may also use URENCO's enrichment capacities dedicated to RepU re-enrichment.

EDF has also decided to open two more reactors (Cruas-1 and -2) to the use of ERU. This project should be carried out in 2009 and could allow to reuse up to 700 tU/year. This is a reversible option since the license for all Cruas NPP units allows to use both ENU and ERU fuels.

However, this recent experience in reactivating the RepU fuel cycle has revealed a number of constraints and limitations which, if they are not overcome, could impact the economy of RepU recycling and its future use.

2.1. RepU storage

Before being recycled, if not recycled on-line in France, RepU has to be stored under a stable chemical form (U_3O_8). EDF's RepU is stored at Pierrelatte.

2.2. Conversion and enrichment

Presently, conversion is possible only in Russia with a limited capacity, but the operating limits in terms of concentration of minor isotopes and impurities allow to process EDF's RepU without known difficulty. Building new conversion facilities will be necessary in the future, and projects which are contemplated in France and in Russia will have to take into account the evolution of the RepU's isotopic composition, which gets more restrictive as the burnup of reprocessed UO_2 fuel increases.

Physical re-enrichment of RepU is possible today in URENCO's facilities at Almelo (The Netherlands) and at Seversk (Russia). Physical re-enrichment should be also offered by AREVA in its future Georges Besse II enrichment plant. At this stage of the fuel cycle, differences between natural uranium and RepU should not be significant. The main difficulty with centrifuge technology is that the enrichment of ^{235}U leads to enrichment of all isotopes lighter than ^{238}U, particularly ^{232}U which is very radioactive, but also ^{234}U and ^{236}U, which are neutron absorbers and make it necessary to increase the enrichment in ^{235}U. Anyway, the actual enrichment needed by EDF should stay under the international limit of 5% ^{235}U by 2015.

Enrichment by blending with uranium previously enriched at a higher assay is a possibility offered mainly by the Russian company TVEL. This approach has been used by several European utilities which recycle RepU. This is a way to avoid high concentrations of minor isotopes in ERU and to end

up with a fuel which is closer to ENU than to physically re-enriched ERU. In any case, it will remain the only possibility to recycle RepU in reactors that would operate with enrichments close to the limit of 5% ^{235}U. However, in order to recycle large quantities of RepU by this route, it should be necessary to implement it in a large number of Light Water Reactors (LWR).

2.3. Purification and fabrication

Purification of the ERU is necessary before fabrication if the time between the filling of the first cylinder and the delivery to the fabrication facility has exceeded a certain period depending on its content in ^{232}U and on the specifications of the fabricator. Gaseous purification is carried out by transfer between UF_6 cylinders. It is a simple but long process (several months per reload). It eliminates ^{232}U decay elements which have been accumulated since the cylinders were filled after enrichment and which are strong gamma emitters. The last ERU reload (URE18 (see Table 1)) and the following ones will use newly produced RepU originated from spent fuel with higher burnups and with more ^{232}U than the previous reloads. As a consequence, purification, which could sometimes be avoided in the past using a just-in-time approach, will be essential. Moreover, when the ^{232}U assay is too high, ERU cannot be stored in the same cylinder beyond a certain duration in order to limit the radiation exposure of the operators when handling empty cylinders. Therefore, if ERU is to be stored for a longer time, it must also be transferred to another cylinder. These operations presently take place in AREVA NC's plant at Pierrelatte. They require a large number of cylinders that will have to be cleaned before re-use.

Fabrication of physically re-enriched ERU takes place in AREVA-FBFC's plant at Romans (France). The specification for the maximum ^{232}U content of this plant (although higher than in other plants that cannot accept re-enriched RepU) are not high enough today to allow recycling RepU batches which came out of the processing plant only in the recent few years. This constraint requires a careful selection and blending of RepU batches in the stockpile, in order to keep the ^{232}U content below the present limitation of the fuel fabrication plant after enrichment. This situation is not sustainable. Thus, without an evolution of the fabrication plant specifications in accordance with ALARA principles, most of the RepU to be produced in the future would not be economically recyclable to produce fuel with energetic equivalence.

2.4. In-reactor performance

The use of RepU in EDF's PWRs is subject to a regulatory limit on the ^{235}U assay which currently is 4.1%. under-performance.

The decline in the quality of RepU due to the increase of burnups at reprocessing is not the only reason why an evolution of some safety limits is considered necessary. Actually, EDF aims at increasing the cycle length of all its reactors, which requires either a higher initial enrichment of the fuel (up to 4.5% or even 4.95% ^{235}U for ENU) or an increased number of fuel assemblies for each reload. In any case, there will be an economic detriment to use ERU fuel instead of ENU fuel. In order to make up for this, the overall price of the fabricated ERU fuel should be lower than the price of the ENU fuel. This "discount" should be related to the difference in energetic capacity of both fuels and to the extra costs borne by the user of ERU fuel.

These difficulties to get the same performance from ERU fuel as from ENU fuel could limit the extension of recycling. More studies will be performed to identify the possibilities for other core managements and the economic interest to recycle RepU on a larger scale.

2.5. Back end

There is no difference between spent ERU and ENU fuels as far as transportation to the reprocessing plant is concerned.

The studies which have been performed by AREVA on the reprocessing of spent ERU fuel do not show difficulties that could not be overcome, even when the content of minor isotopes in the ERU is increased.

3. Conditions for the development of a RepU market

There are significant RepU inventories in different countries, and EDF clearly owns one of the largest ones. This RepU could be reused economically and help to reduce the need for natural uranium in the future. However, this will be possible only if suppliers of nuclear fuel services are able to overcome present limitations and to offer additional capacities for the production of ERU fuel at competitive prices.

Higher burnups of ENU fuel lead to an increased concentration of minor isotopes in the recovered RepU and make it more difficult to recycle RepU. In order to get round these obstacles, technical solutions must be found and investments may have to be made in the front end part of the ERU fuel cycle:

- New conversion facilities are needed.
- New enrichment capacities are also needed. The centrifuge technology, because it is modular, allows to devote specific cascades to RepU enrichment, which is not possible with gaseous diffusion. However, laser techniques, if they are available at an industrial scale, could allow selective re-enrichment of ^{235}U and could find with ERU a first economic application.
- Suppliers and utilities should also work together in order to increase the present limit of 5% ^{235}U enrichment in the international regulations and standards, at least for ERU fuel.
- The specifications of fabrication plants must be reassessed so that they can accept ERU with a higher ^{232}U assay.

When the natural uranium prices are rising, as the total cost of ERU fuel is naturally disconnected from the price of natural uranium, ERU fuel cost should be lower than the cost of ENU fuel, which is a necessary condition for ERU fuel to be competitive. In order to keep the prices for ERU fuel assemblies low, another condition for the development of a RepU market is probably some degree of competition and a bigger market. The opening of the closed cycle option in some countries (like the USA) or its further development in other countries where it already exists (like Japan, Russia or the UK) would certainly help reaching this goal.

Neutronic aspects of in-core fuel management with enriched reprocessed uranium – Belgian experience

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Abstract. Enriched reprocessed uranium (ERU) has been loaded in the Belgian Doel-1 reactor up to 100% of the core with no specific licensing requirement. The lack of reactivity resulting from the ^{234}U and ^{236}U content needed to be compensated by an over-enrichment, or, at constant enrichment, by additional fresh fuel assemblies. Comparison with similar 'in-core fuel management' (ICFM) (same cycle length, same enrichment) performed with enriched natural uranium (ENU) shows that the impact of ERU on the main neutronic parameters is small, or has the same order of magnitude as the change in ICFM. The dose rate of fresh ERU (although initially non significant), increases with time. Therefore, it had been recommended to store fresh ERU fuel assemblies in the pool and not in dry storage. Finally, the main restriction comes from the ^{232}U content, and time delay between conversion and transport becomes relevant.

1. Introduction

In Belgium, there are 7 nuclear power plants (NPPs) in operation on the sites of Doel (4 units) and Tihange (3 units), with a total capacity of about 6000 MW(e). They produce about 60% of the total electricity in the country. Those NPPs are all Westinghouse or Framatome designed Pressurized Water Reactors (PWR), which were built during the 1970s and 1980s. In particular, Doel-1 and -2 are twin units, with two loops and 121 fuel assemblies. The assembly lattice equals to 14x14 rods with an 8 feet active length. Their thermal power was initially 1192 MW•th, but it has been up-rated by 10% in Doel-2 when the steam generators have been replaced in 2004 (beginning of cycle 31).

All the plants are operated by Electrabel, which is a division of the Suez Group and the largest utility in Belgium. The architect engineering and operational engineering support are provided by Tractebel Engineering which is also a division of the Suez Group.

Reprocessing was the design assumption for the Belgian NPP units. Most of the spent fuel of the first 12 cycles of the three oldest ones (irradiated between roughly 1974 and 1991) has been sent to COGEMA's reprocessing facilities at La Hague. The reprocessed U and Pu have been recycled in Belgian units:

- Pu has been mixed with uranium (MOX) and reloaded in Tihange-2 and Doel-3.
- Reprocessed uranium (RepU) has been re-enriched. The enriched reprocessed uranium (ERU) has been introduced in a full reload in Doel-1 from 1994 (cycle 21) to 2003 (cycle 30). Meanwhile Doel-2 went on being loaded with enriched natural uranium (ENU).

The Belgian government voted a moratorium on reprocessing in 1993. The then existing reprocessing contracts went then on to their end, but no new one has been signed. Therefore, after the loading of the last ERU fuel assemblies in 2003, Doel-1 went back gradually to full ENU fuel reloads, and it now has again a full ENU fuel core.

2. Isotopic content

The average discharge burnup of the reprocessed assemblies ranges from 12 and 24 GWd/t HM for the first two batches, to 36 GWd/t HM for the next ones.

The typical isotopic content of the discharged ENU fuel assemblies is as follows:

^{232}U	1.37 ppb
^{234}U	0.018%
^{235}U	0.83%
^{236}U	0.418%

And this is the typical composition of fresh ERU fuel assemblies with an enrichment of 3.8% ^{235}U equivalent:

^{232}U	9.8 ppb
^{234}U	0.11%
^{235}U	4.25%
^{236}U	1.5%

3. Dose rate

The main radiological limitations after enrichment come from the residual content of the next two even isotopes that are more re-enriched than ^{235}U in the centrifugation process:

- ^{232}U yields ^{212}Bi and ^{208}Tl, two hard gamma emitters.
- ^{234}U is an alpha emitter that is responsible for 80% of the radioactivity of ERU.

These isotopes lead to restrictions (limits) in fuel fabrication:

- Even if alpha radioactivity is rather high, the protection of the workers is achieved by rather simple means and rules. The licensed limit of the AREVA fabrication facility at Romans (France) is 0.15%.
- Gamma radioactivity is much more limiting, and therefore, the ^{232}U content was limited to 10 ppb at the time of the ERU recycling in Doel-1, which was very close to the mentioned typical content of the ERU.

Gamma radioactivity leads also to restrictions (limits) in the handling of the fuel assemblies on the site. At the time of its fabrication, the gamma radioactivity of an ERU fuel assembly is almost 1.5 to 2 times higher than the one of an ENU assembly, and it can be more than 5 times higher at the time of its delivery on-site. Nevertheless, it remains low (typically 0.25 mSv/h in contact of the fuel assembly and 0.06 mSv/h at 1 meter from an open container with two fuel assemblies), but it still increases with time due to the accumulation of the ^{232}U daughter products as indicated in Fig. 1.

This Figure shows the dose increase related to 10 ppb ^{232}U. Time delay between conversion and fuel delivery also becomes a relevant parameter, and the fresh assemblies should preferably be delivered within the four months following the ERU conversion.

Therefore, no supplementary shielding is needed for ERU fuel on-site delivery, and the handling procedures remain the same as for ENU assemblies. Nevertheless, as a conservative approach the fresh ERU assemblies are directly stored in the pool and never in dry storage.

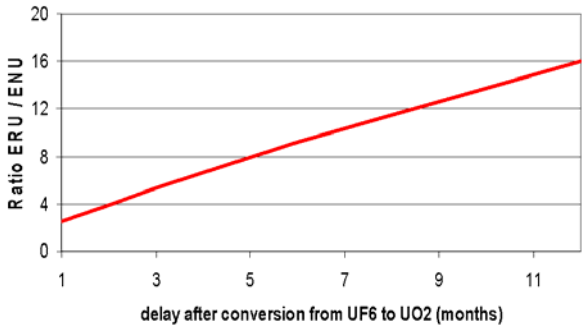


FIG. 1. Ratio of gamma dose rate of ERU to that of ENU versus delay after conversion from UF_6 into UO_2.

4. Neutronic impact

The neutronic characteristics of the ERU are mainly impacted by:

- the ^{234}U content, as this isotope is fertile; and
- ^{236}U which is a neutron thermal absorber.

As a consequence of the significant ^{236}U content, the calculation route needed to be adapted in order to correctly evaluate the Doppler effect: The resonance treatment of the ^{236}U isotope has been made dependent on temperature in the assembly calculation code, as it is possible in LWR-WIMS (WIMS = Winfrith Improved Multigroup Scheme). The adequacy of this treatment has been confirmed by the good accuracy of the measured values (namely the power defect through the boron concentrations versus power).

4.1. Impact on the safety

It must be verified that the engineering factor considered in F_Q calculation remains consistent with ERU fabrication tolerances. A sensitivity study has been performed that shows the negligible impact of ^{234}U and ^{236}U on the peaking factor which justifies the applicability of the same value as for ENU to cover the fabrication tolerance on ^{234}U (±500 ppm) and on ^{236}U (±1000 ppm).

4.2. Equivalence principle

The basis of the equivalence principle is that ERU should give the same cycle length as ENU.

Let us make, therefore, the simplifying assumption that the core reactivity equals the average reactivity of all the assemblies loaded in the core. Knowing that the assembly reactivity is nearly linear versus burnup, it can be concluded that, in order to keep the cycle length unchanged with a similar ICFM, the reactivity of ERU and ENU assemblies must be identical at the end-of-cycle (EOC) core average burnup in this ICFM.

Therefore, on one hand, the absorbing effect of ^{234}U and ^{236}U must be compensated by additional enrichment and on the other hand, because ^{234}U acts like a burnable poison, the reactivity curve versus burnup is flatter for ERU than it is for ENU.

Thus, with a higher enrichment the begin-of-cycle (BOC) reactivity is lower for ERU than for equivalent ENU which is favourable for critical boron and moderator temperature coefficients. For the Doel-1 annual ICFM, ERU enrichment needed to be 4.25% to be equivalent to the 3.8% ^{235}U of the ENU assemblies at the time of the first introduction, which was the highest enrichment compatible with the fuel rod capability (burnup). Figure 2 shows the assembly k-infinity versus burnup for resp. 3.8% ENU and 4.25% ERU.

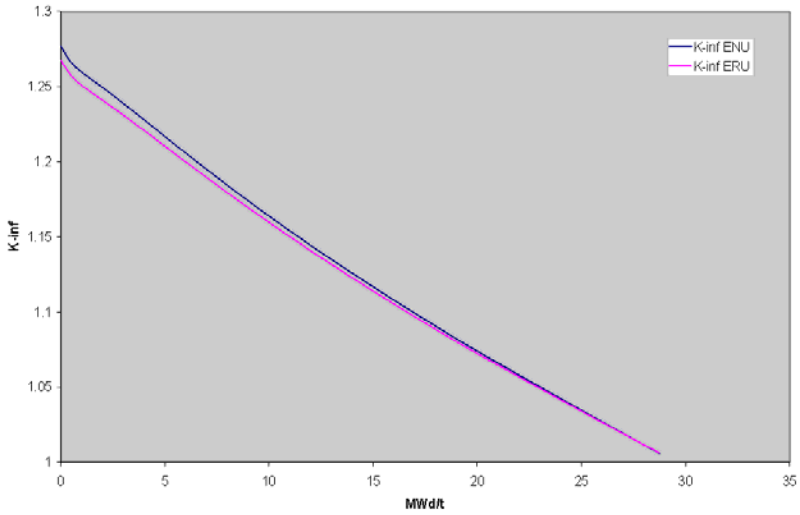


FIG. 2. Fuel assembly k-infinity versus burnup for ENU (3.8% ^{235}U) and ERU (4.25% ^{235}U).

4.3. In-core fuel management

Doel-1 and -2 are operated in annual cycles. The typical loading patterns are presented in Fig. 3 for Doel-2 and in Figure 4 for Doel-1.

In Doel-1, full ERU feed has been loaded from cycle 21 to cycle 29. Cycle 25 was the second full ERU core. Note that a single ENU reload has been introduced at cycle 28. Full ENU feeds came back from cycle 31 on.

In Doel-2, the enrichment has progressively increased from 3.9% ^{235}U in cycle 24 to 4.0% ^{235}U in cycle 25, and to 4.25% ^{235}U from cycle 26 on. It increased again from cycle 31 on, after power uprate.

Thus, from cycle 26 to 30 the enrichment was the same in both cores (Doel-1 and -2), and the lack of reactivity of the ERU assemblies relative to the ENU ones has been compensated by a larger feed batch.

Figure 5 summarizes the feed characteristics. Figure 6 shows the begin of cycle (BOC) boron concentration and the total cycle length (stretch out included). The cycle length variation from one cycle to the next one depends on the needs of the Belgian electricity grid and on calendar constraints.

Cycle 27 in Doel-1 and cycle 29 in Doel-2 are almost in equilibrium (white symbol on the figures).

FIG. 3. Doel-2 loading pattern: Alternatively 28 and 32 fresh ENU fuel assemblies.

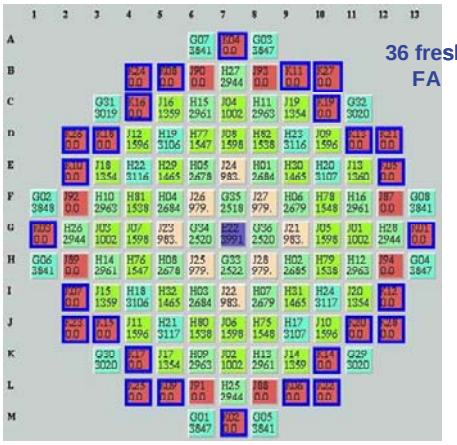


FIG. 4. Doel-1 loading pattern: 36 fresh ERU fuel assemblies.

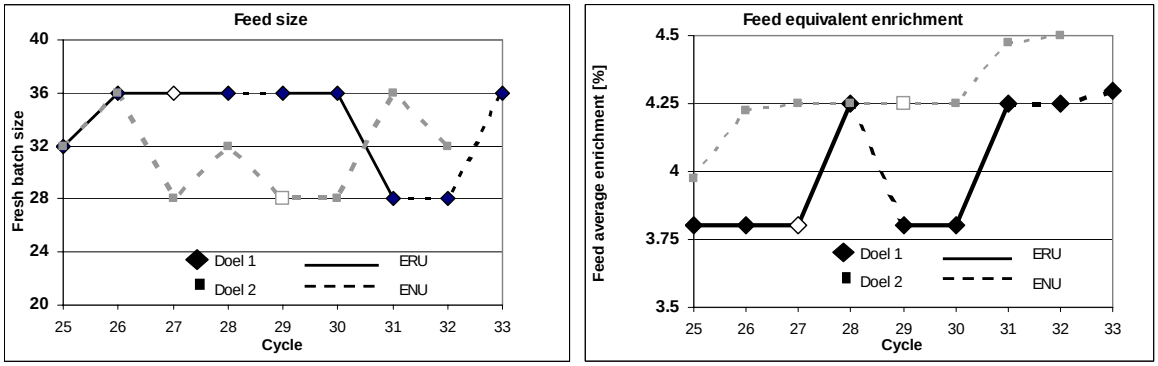


FIG. 5. Feed sizes and equivalent enrichments of ENU and ERU fuel in Doel-1 and -2 (by cycle).

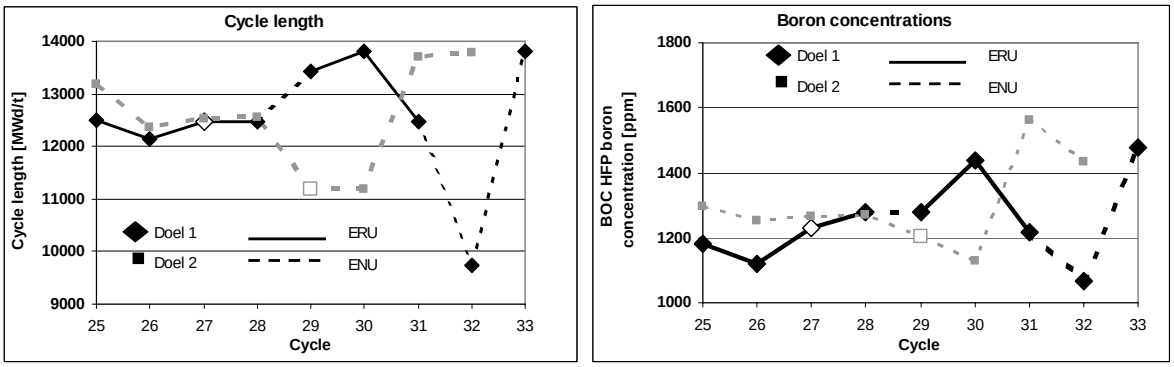


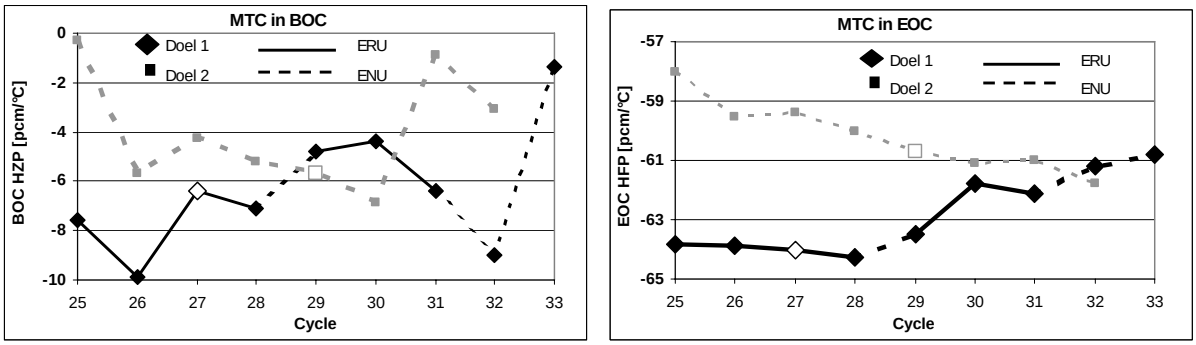
FIG. 6. Cycle lengths and full power boron concentrations of ENU and ERU fuel in Doel-1 and -2 (by cycle).

In the following sections of this paper, the main neutronic parameters of both NPP units are compared on cycles 25 to 33 (Doel-1) or 25 to 32 (Doel-2). The comparison between the equilibrium cycles (white symbols) shows the effect of ERU, which is related to the normal variation due to the ICFM (differences between successive cycles of each unit).

4.4. Impact on nuclear key safety parameters (NKSP)

The main differences of the nuclear key safety parameters (NKSP) come from the higher absorption in thermal and epithermal energy ranges, with stronger moderator temperature coefficients (MTC) and Doppler temperature coefficients as main consequences, but in a very limited amount.

Figure 7 shows MTC at BOC and EOC. As long as the Doel-1 core was fully loaded with ERU and as long as the cycle length was similar with Doel-2, MTC in Doel-1 was less than 1 pcm/°C more negative at BOC than in Doel-2. This difference is by far smaller than the normal variation due to ICFM itself.



HZP = Hot Zero Power

HFP = Hot Full Power

FIG. 7. Begin of cycle (BOC) and end of cycle (EOC) moderator temperature coefficients of ENU fuel and ERU fuel in Doel-1 and –2 (by cycle).

The Doppler temperature is most affected by ERU. Figure 8 shows the evolution of the Doppler coefficient in BOC HZP conditions:

- In Doel-1, it is clear that as long as the core is fully loaded with ERU, the 'Doppler effect' is stronger, but as soon as the ERU content decreases in the core, the 'Doppler effect' decreases again. Therefore, it was necessary to take a bit more margin in the licensing studies on that coefficient.
- In Doel-2, the 'Doppler effect' stabilises at about -3.4 pcm/°C when the full core is loaded with 4.25% ENU.

The effect of ERU can thus be evaluated to -0.3 pcm/°C for the same enrichment.

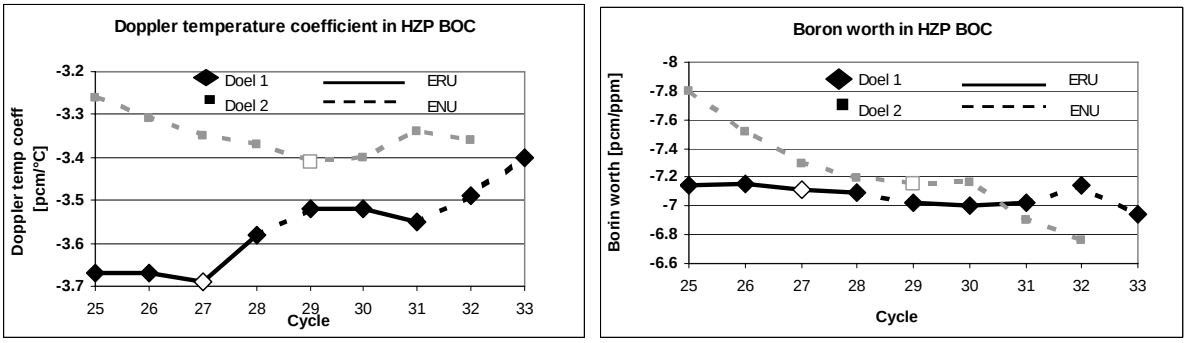


FIG. 8. Evolution of Doppler coefficient in Hot Zero Power Begin of Cycle (HZP BOC) in Doel-1 and –2 (by cycle).

The evolution of the boron worth in Doel-2 is also related to the evolution of the enrichment in the core. It stabilises at about -7.1 pcm/ppm, just the same value as in case of an ERU equilibrium core. So the main effect is more related to the ^{235}U content than to the other isotopes.

The control rod worth is affected by ERU, but with the same order of magnitude as the loading pattern itself.

Finally, the shutdown margin is usually smaller for an ERU fuel core than for an ENU one. One reason is the lower rod worth, but the loading pattern plays also a significant role.

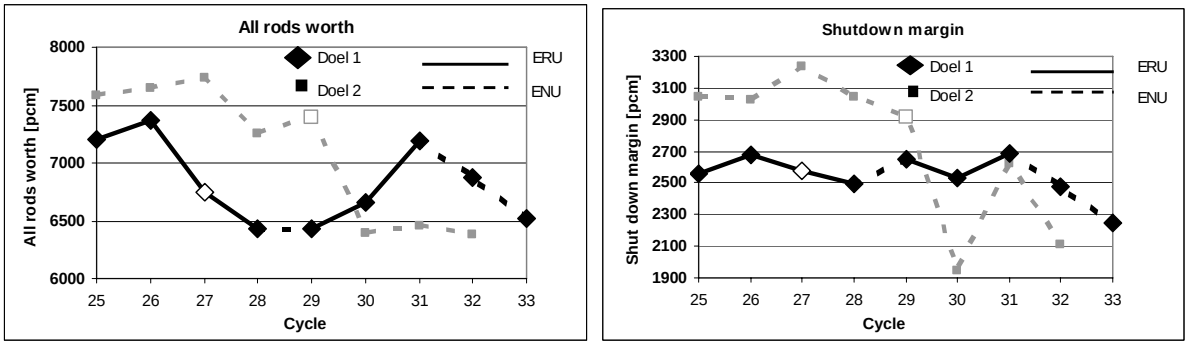


FIG. 9. Rod worth and shutdown margin of ENU and ERU fuel in Doel-1 and –2 (by cycle).

5. Impact on the fuel design

On one hand, the harder neutron flux has a small impact on grid skeleton growth and grid spring behaviour, but in a negligible amount regarding the available margins.

On the other hand, the neutronic differences are too limited to have any impact on the neutronic compatibility and design.

6. Conclusion

The introduction of a full ERU reload in Doel-1 has been performed without significant impact:

— No specific licensing was required except that the FQ engineering factor had to be justified.
— Available margins on nuclear key safety parameters were sufficient to cover the small impact of ERU (smaller than the normal variation due to ICFM changes).
— No fuel handling procedure change was necessary, except that fresh fuel is directly stored under water in the pool.

Thirty years of experience with reprocessed uranium management in Borssele

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Abstract. The Borssele NPP (start-up in 1973) is the only operating Nuclear Power Plant (NPP) in the Netherlands. In 1976, the first contract for reprocessing its spent fuel in the La Hague reprocessing facility was signed, and subsequent reprocessing contracts cover fuel arisings until 2015. Borssele's owner-operator, EPZ, has the option to continue reprocessing until the agreed final plant closure in 2034. Reprocessing results in the annual production of 10 tonnes reprocessed uranium (RepU) on average. Legally the long-time storage of RepU in France is possible under certain conditions. Other options for the management of EPZ's RepU arisings are the transfer of title to third parties, the re-enrichment of RepU and its use for the production of enriched reprocessed uranium (ERU) fuel assemblies and the long-term storage in the Netherlands. In the first twenty years of plant operations, EPZ's RepU has either been returned to the enrichment plant or has been sold off. More recently, EPZ has decided to recycle its RepU in its own reactor in Borssele. This recycling has been implemented since 2003. EPZ has no stockpiles of RepU. Initially, a barrier against recycling in fresh fuel was that the fuel fabricator was not licensed to handle enriched uranium other than from natural feedstock. This barrier could be circumvented by co-operation with the company OAO Mashinostroitelny Zavod (MSZ) at Elektrostal (Russia) *via* a contract with AREVA NP. MSZ has enriched batches of EPZ's RepU and has produced the UO_2 pellets for two reloads of the Borssele reactor. EPZ has also the option of long-term storage of its RepU at the COVRA site. COVRA is the organisation for intermediate storage of radioactive (waste) materials in the Netherlands. COVRA is licensed to take title of, and to store, uranium oxide. It has a dedicated facility to do so. EPZ's decision to recyle and not to dispose of RepU was based on economical arguments. However, this decision was in line with the company's policy to minimise waste for disposal and to recycle materials whenever possible. It is a good result that economical arguments actually favour the recycling option. EPZ is quite transparent in its selected fuel strategies. In the Netherlands, the nuclear fuel cycle is subject to governmental and public scrutiny. As a result of recent lawmaking in France, the intention to recycle reprocessed uranium will have to be confirmed by the respective governments of the Netherlands and France in the form of an intergovernmental agreement. Such an agreement is presently under negotiation.

1. The Borssele NPP

The Borssele nuclear power plant (NPP) is the only operating commercial power reactor in the Netherlands. It is owned and operated by N.V. Elektriciteits-Produktie-Maatschappij Zuid-Nederland (EPZ) which also operates a 405 MW(e) coal-fired electricity plant at the Borssele site (Figure 1). EPZ's nuclear unit is a 481 MW(e)(net) pressurized water reactor (PWR) of KWU design. The reactor came into operation in 1973.

The Borssele NPP is in a good technical condition. Its average availability factor since 2000 has been 92.7%.

In 1997, major safety upgrades have been implemented that ensure that the plant design features meet today's safety requirements for new nuclear build.

In 2006, a formal agreement has been closed with the Netherlands' government that the plant will be allowed to operate until 2034, which is equivalent to a 60 year lifetime. EPZ expects that the unit will successfully reach this age, given its present good technical condition and EPZ's active equipment ageing management program.

FIG. 1. The Borssele nuclear and coal-fired power plants.

2. Borssele fuel cycle information

The Borssele NPP uses uranium oxide fuel and is operated with a 12-month cycle. The average discharge burnup, which during most of its operating history was only 32 MW•d/kg U, has in recent years been increased to 50 MW•d/kg U and is set to reach 55 MW•d/kg U. To obtain this improvement the ^{235}U assay has been increased from the original 3.3% in steps, from 2001 to 2005 to 4.4% ^{235}U.

The Borssele nuclear fuel is being fabricated in Germany, in the facility of Advanced Nuclear Fuels GmbH (ANF) at Lingen. After irradiation, it is reprocessed in AREVA NC's facilities at La Hague (France). There are no facilities in the Netherlands for the direct storage of spent fuel from power reactors; reprocessing abroad is presently the only back end option.

However, the national government has announced that it wants a review of the benefits of the reprocessing option (such as materials recycling), and that it will introduce a licensing system for future reprocessing contracts.

3. Management of past quantities of reprocessed uranium

Radioactive waste in the Netherlands is being managed by the state-owned organisation COVRA, which has its site only a few kilometers form the Borssele reactor. Residues from reprocessing of spent fuel are being stored in COVRA's intermediate storage facility for high level-waste, HABOG. COVRA has also facilities for the storage of low-level waste and for the storage of uranium oxide[1].

FIG. 2. The HABOG facility for the storage of high-level radwaste.

[1] Quantities of depleted uranium oxide have been transferred for long time storage to COVRA.

Reprocessing of spent fuel from the Borssele NPP in the La Hague facilities started in 1976. Since then, about 310 tonnes of RepU have arisen from this reprocessing. This uranium has been converted to UF_6 or U_3O_8 in the Pierrelatte (France) plant, where it has been temporary stored until a destination was identified.

Until 1987, enrichment services for the annual Borssele reloads were provided by the US Department of Energy (DOE), and the DOE accepted returns of RepU as feedstock for its gaseous diffusion plants in Paducah and Oak Ridge[2]. DOE used to mix RepU (to less than 1% of the total flow) with the feed to its gaseous diffusion cascades. At that time, the RepU from power reactors was positively valued because of its residual enrichment (1.0–1.4 w/o ^{235}U) and its low burnup (resulting in a low ^{236}U content). This re-enrichment procedure ceased when the Borssele NPP discontinued the enrichment contract with DOE and replaced it by a contract with URENCO. In the same time frame, DOE decided to discontinue the practice of enriching recycled uranium altogether.

In the 1990s, it appeared more difficult to re-use RepU. The market price for virgin uranium at the time was historically low, making the RepU less attractive. Re-enriching RepU affects its quality as reactor fuel. Because in the URENCO centrifuges RepU is not being diluted with natural uranium, the enriched reprocessed uranium (ERU) would be significantly tainted with nuisance isotopes, such as ^{232}U and ^{236}U. This issue will be elaborated below. Another complication was that the German fuel fabrication plant was not licensed to handle ERU. However, in 2003 ANF has obtained such a license.

EPZ at that time decided not to recycle its uranium in the Borssele reactor. Instead, it identified other nuclear operators who were already re-using RepU on an industrial scale, and some batches of EPZ's RepU were transferred to those other users, at prices lower than the market price for natural uranium.

FIG. 3. AREVA NC's reprocessed uranium storage at Pierrrelatte (France).

Since 1993, the fuel manufacturer Siemens AG (today: AREVA NP) has been co-operating with the Russian company MSZ for the production of fuel from RepU for the W(e)st European market. Because MSZ uses the process of blending RepU with highly enriched uranium (HEU), the problem of nuisance isotopes in the final product is much reduced. Since 2003, EPZ has used all its RepU arisings (about 90 tonnes so far) for the production of Borssele reloads by MSZ's plant at Elektrostal.

The fuel which has been assembled at Elektrostal is performing well in the reactor. Some of it is now in its fourth operating cycle. EPZ expects that these ERU fuel assemblies will reach a burnup of ~ 50 MW•d/kg U. This is marginally lower than the burnup of ENU fuel for reasons that will be explained hereafter.

The RepU which EPZ has still left in storage in the conversion plant at Pierrelatte is a small quantity – a few tonnes - with Euratom obligation codes that make it legally difficult to export it to Russia. This

[2] On 29 March 2001, the DOE released 9 site-specific studies that examined the historic use of recycled uranium in its facilities. These studies demonstrate that European reprocessors shipped significant quantities of RepU between 1969 and 1988 for re-enrichment in the USA.

has to do with cold-war era treaties closed between the Euratom Supply Agency (ESA) and the USA and Canada. These treaties prohibit the re-export of fissile materials with "American" or "Canadian" obligations to the former Soviet Union countries. Certainly, in time, this obstacle will be solved.

In short, EPZ has no significant legacy of RepU, and the subject of re-using RepU is presently of interest for future RepU arisings, not for the past ones.

4. Expected quantities and qualities of RepU arisings

When existing reprocessing contracts between EPZ and AREVA NC will have been fully implemented, another 100 tonnes of RepU are to be produced until about 2017[3]. In case a decision would be made to continue reprocessing until the final shutdown of the Borssele NPP in 2034, about 200 extra tonnes of RepU would become available until 2040. For a single-reactor operator like EPZ these are significant quantities to manage.

Characteristics of the future arisings will be:

- A gradual change in the isotope vector. Most of EPZ's previous RepU was typical of medium burnup quality (~ 32 MW•d/kg U), but the average burnup will be ramped up to something between 50 and 55 MW•d/kg U.
- Part of the future RepU will be recovered from EPZ's irradiated RepU-based fuel. At the moment, one fourth of the Borssele reactor core is made up of recycled uranium. There is little experience – as far as EPZ is aware – with the properties of second-generation RepU.
- Possibly, EPZ will begin the recycling of its plutonium as MOX fuel. Presently, its plutonium arisings are being transferred for MOX used in foreign reactors. The uranium component in reprocessed MOX fuel will have different properties from the present-day first-generation RepU.

Generally, it must be anticipated that the quality of EPZ's RepU will detoriate somewhat over time, depending on the progress in fuel burnup values and with the increased use of second-generation heavy metals. There is no reason to expect that this detoriation will stand in the way of some form of re-use of the material.

5. In-core effects of nuisance isotopes

The 232U and 234U isotopes are mostly unwanted for health protection reasons. The most important undesirable isotope for reactor operations is 236U, which is a strong thermal neutron absorber. As a rule of the thumb, reactor engineers assume that the reactivity of a fuel assembly (expressed as its 235U content) is reduced by one-third of its ^{236}U content.

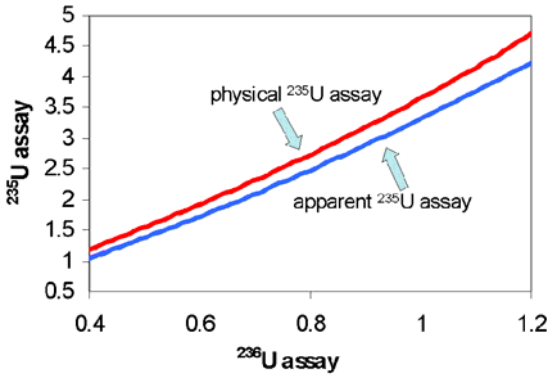

FIG. 4. Co-enrichment of ^{235}U and ^{236}U (in w/o) with the resulting apparent ^{235}U assay remaining below the physical ^{235}U assay.

[3] Due to legal complications, the reprocessing of Borssele spent fuel has been temporary stalled but is expected to resume within one or two years.

Thus, a fuel assembly with an enrichment of 4.4% ^{235}U, but a 1.1% ^{236}U contamination, will perform in the reactor like a 4.0% ^{235}U enriched assembly.

In an enrichment plant, ^{235}U and ^{236}U will both be concentrated in the product, as Figure 4 shows for one specific example. If one starts with RepU feed of 1.2% residual ^{235}U and a 0.4% ^{236}U contamination, the 4.4% ^{235}U enriched product will contain 1.1% ^{236}U as well.

The lower line in Fig. 4 gives an indication of the apparent reactivity of the fuel, which is lower than the physical ^{235}U enrichment because of the effect of the ^{236}U neutron absorbers.

The most usual method to compensate the effect of these neutron absorbers is to enrich the ^{235}U somewhat further. To produce ERU fuel with an apparent enrichment of 4.4% ^{235}U, one might be obliged to actually enrich RepU up to 4.8%, which incurs the cost of 13% extra separative work. This increases the price of the reactor reload by about 4 or 5%.

This compensation method is not feasible for the Borssele NPP, for formal reasons. The operational license explicitly limits the ^{235}U assay of the fuel to 4.4 ± 0.05%.

For that reason, the lower reactivity of ERU fuel must be compensated by a greater size of reloads, or by accepting a shorter natural cycle length. For instance, a ^{236}U contamination of about 1% might be compensated by increasing the size of a Borssele reload from 28 to 32 fuel assemblies. This results in a reload that costs about 14% more to purchase. Increasing the size of the reload, as Borssele is obliged to do, is clearly a less efficient compensation method than the method of extra ^{235}U enrichment.

6. The method of enrichment by blending

Since more than 10 years, the fuel fabricator AREVA NP has co-operated with MSZ to use RepU for the downblending of fissile materials. The resulting low enriched uranium is being used to produce reactor fuel for W(e)st European reactors. The major advantage of the blending process for the reactor engineers is that co-enrichment of ^{235}U with ^{236}U and other nuisance isotopes is being avoided. The Borssele NPP has been receiving fuel with a contamination of ~0.4 w/o of ^{236}U, while the same uranium, if enriched by conventional methods, would have contained ~ 1.3 w/o ^{236}U. The production process of fuel assemblies at Elektrostal involves higher costs than the conventional production in ANF's plant at Lingen, but this is partially compensated by this lower ^{236}U content.

FIG. 5. Receiving ERU fuel in the Borssele NPP.

Still, the ERU fuel has a reduced reactivity in comparison to the standard ENU fuel. This results in a lower average burnup level at reactor discharge. EPZ expects that on average an ERU fuel assembly will reach a burnup which is 2 – 3 MW•d/kg U below that of an ENU fuel assembly with the same ^{235}U enrichment.

7. Future options for managing reprocessed uranium

EPZ faces the challenge of managing future quantities of RepU:

- 100 tonnes will be produced between 2008 and 2018, on the basis of existing reprocessing contracts. This quantity will have a somewhat higher burnup than quantities discharged years ago.
- If the reprocessing process would be continued for the residual lifetime of the Borssele NPP, there would be another 200 tonnes. One third of that quantity would be produced from the final core and the final fuel pool inventory, after reactor shutdown.

EPZ has identified the following options for managing these future RepU arisings:

- Re-enrichment using the downblending process, and recycling of the fuel in the Borssele reactor.
- Re-enrichment of the uranium in an enrichment plant, and recycling of the fuel in the Borssele reactor.
- Transfer of title to third parties, who intend to re-use the material themselves.
- Long-term storage of the uranium in France as oxide or fluoride.
- Transfer to COVRA in the Netherlands, to be stored long-time as oxide.

The above is also roughly the sequence of preference, depending on commercial conditions which will be evaluated for each separate batch. Of course, the first two options for recycling in Borssele are only available as long as the plant is operating; they will disappear in 2034. Thus, other options than recycling must be used as well.

Recycling of uranium in EPZ's own reactor is the preferred option because it is consistent with the justification of reprocessing as the best back end process. Reprocessing is about recycling of materials. The decision for reprocessing as the preferred back end option may be based on economical evaluation, but it is risky without strong and publicly accepted justification. There are many stakeholders in the civil society and in politics that must support reprocessing of spent fuel. For every step in the process, licenses and agreements are needed, such as transport licenses, fuel export licenses and agreements to store materials (reprocessing residues) at the COVRA facility. As long as the utility EPZ can demonstrate that it is really recycling fissile materials, the public case for spent fuel reprocessing will be stronger. So, EPZ will try to recycle RepU unless the economics are strongly biased against it.

Transfer of RepU to other nuclear operators is probably still an available option, but EPZ has not actively investigated it recently. The rising market prices of natural uranium have improved the commercial attraction of RepU. Therefore, it should be expected that buyers can be found.

Long- time storage in France is theoretically possible, since the new French law of June 2006 does not prohibit it. However, the material would be a long-term legal liability for EPZ, making this option relatively unattractive. It is not known if such long-term storage services are commercially available anyway.

In case EPZ would decide to transfer it RepU to COVRA, the title would also be transferred to COVRA. That would relieve EPZ from its liability. However, this would effectively declassify the uranium as a resource and would reclassify it as radioactive waste. That would run counter to the justification of reprocessing as a recycling approach. Therefore, the option of transferring uranium to the waste management organisation must be seen as the option of last resort.

Given the past experience in management of its RepU arisings, EPZ is confident that it will also succeed for the future quantities. Uranium is not perceived as a major obstacle in the pursuit of a long-term reprocessing policy.

Reprocessed uranium recycled in PWRs: Impact on the core of reactor and on the fuel cycle

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Abstract. The presence of ^{234}U and ^{236}U requires-over enrichment in ^{235}U for the recycling of the reprocessed uranium (RepU) in PWRs in the form of UO_2 fuel. For burnup rates of 55 GW•d/t HM, the required ^{235}U assay of enriched reprocessed uranium (ERU) fuel very quickly reaches 5% with traditional processes like ultra centrifugation. The emission of γ radiations by the decay products of ^{232}U requires significant biological protections for all the operations in the front end of the nuclear fuel cycle. The recycling of the reprocessed uranium increases the production of Pu by approximately 10% with a strong increase of ^{238}Pu which will have an impact on thermal power in the processes of the fuel reprocessing. The production of neptunium is also significantly increased up to a factor of 4. The production of curium is slightly decreased. The first recycling of the reprocessed uranium in PWR would allow reducing the needs for natural uranium by approximately 10%.

1. Introduction

The closed nuclear fuel cycle option results in recovering the uranium and the plutonium containing fissile isotopes which may increase the potential value in a nuclear reactor to produce energy. The object of this paper is to show the possibilities of recycling of uranium resulting from the standard UO_2 fuel reprocessing (reprocessed uranium) and to evaluate the impact on the core of the reactor and during operations of the fuel cycle. The aim of the study is:

- to present the various isotopic compositions and their evolutions during the ageing of reprocessed uranium;
- to evaluate the ^{235}U enrichment necessary for the recycling of this reprocessed uranium in the PWRs;
- to evaluate the impact of the production of γ radiations during various operations in the upline cycle;
- to calculate the characteristics of the various elements produced in irradiated enriched reprocessed uranium (ERU) fuel; and
- to evaluate the potential gain on natural uranium for a nuclear park made up of PWRs.

2. The reprocessed uranium

2.1. The characteristics of uranium

Two types of uranium are studied:

- RepU resulting from UOX fuel, enriched initially to 3.25% ^{235}U and irradiated until 33 GW•d/ HMt,
- RepU resulting from UOX fuel, enriched initially to 4.50% ^{235}U and irradiated until 55 GW•d/t HM.

The uranium composition is given in Table 1 according to the time of cooling before the reprocessing of the spent fuel, with the time of ageing between the enrichment of the RepU and the introduction of the ERU fuel into the reactor core being 2 years.

TABLE 1. ISOTOPIC COMPOSITION EVOLUTION FOR REPU

Burnup (GW•d/t HM)	Cooling Time (years)	^{232}U (%)	^{234}U (%)	^{235}U (%)	^{236}U (%)	^{238}U (%)
33	3	1.21E-07	1.98E-02	9.15E-01	4.05E-01	9.87E+01
	5	1.37E-07	2.00E-02	9.15E-01	4.05E-01	9.87E+01
	10	1.51E-07	2.06E-02	9.16E-01	4.05E-01	9.87E+01
55	3	3.78E-07	2.22E-02	7.85E-01	6.43E-01	9.85E+01
	5	4.27E-07	2.29E-02	7.85E-01	6.43E-01	9.85E+01
	10	4.70E-07	2.46E-02	7.85E-01	6.43E-01	9.85E+01

Compared with natural uranium, the RepU resulting from irradiated UOX fuels contains all the isotopes of uranium. Only the following isotopes are to be considered for recycling:

- ^{234}U and ^{236}U which have a negative impact on the physics of the core increase with the burnup.
- ^{232}U which has an impact on the physics of the cycle (γ radiations), increases with the burnup and the time of cooling before reprocessing (disintegrations of the ^{236}Pu).
- ^{235}U which is fissile decreases with the burnup.
- The majority of the ^{238}U remains stable.

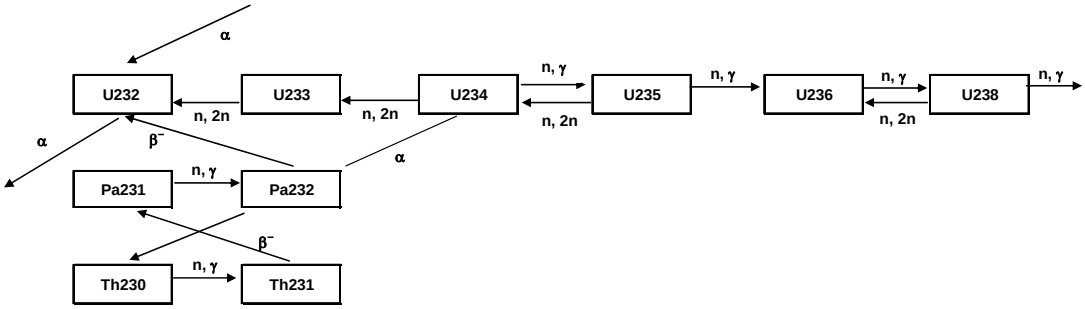

FIG. 1. Chains of the formation of ^{232}U under irradiation.

Under irradiation, the major part of ^{232}U is formed by successive reactions (n, 2n) of ^{234}U, but also by successive reactions (n, γ) of ^{230}Th formed by the α decay of ^{234}U during the ageing of enriched uranium. For a 2 years ageing, the formation of ^{232}U by this way varies between 20% and 30% (Fig. 1).

2.2. Impact on the radioprotection in the front end cycle

Tables 2 and 3 give the evolution of the spectrum, by group of energy, and of the γ radiation source of reprocessed uranium, according to the cooling time after the UO_2 fuel reprocessing.

TABLE 2. EVOLUTION OF THE SPECTRUM (%) AND THE SOURCE (γ/s/metric tonne U) of γ RADIATIONS FOR THE REPU FROM THE TREATMENT OF A UO_2 FUEL (33 GW•d/t HM, cooled 10 years)

cooling time (years)		1	3	5	7	10	15	20	30	50
High E (ev)	Low E (ev)									
3.5E+06	3.0E+06	9.8E-10	7.3E-09	1.9E-08	3.6E-08	7.2E-08	1.6E-07	3.0E-07	6.9E-07	2.1E-06
3.0E+06	2.5E+06	4.7E+00	8.3E+00	9.5E+00	1.0E+01	1.0E+01	1.0E+01	9.8E+00	9.2E+00	8.1E+00
2.5E+06	2.0E+06	2.9E-07	2.2E-06	5.6E-06	1.1E-05	2.1E-05	4.9E-05	8.8E-05	2.1E-04	6.1E-04
2.0E+06	1.7E+06	3.1E-01	2.8E-01	2.8E-01	2.7E-01	2.7E-01	2.7E-01	2.8E-01	2.8E-01	2.9E-01
1.7E+06	1.5E+06	3.4E-01	5.0E-01	5.5E-01	5.7E-01	5.8E-01	5.7E-01	5.6E-01	5.4E-01	4.9E-01
1.5E+06	1.3E+06	7.3E-02	6.0E-02	5.5E-02	5.3E-02	5.3E-02	5.3E-02	5.4E-02	5.6E-02	6.1E-02
1.3E+06	1.0E+06	2.8E+00	2.4E+00	2.2E+00	2.2E+00	2.2E+00	2.2E+00	2.2E+00	2.3E+00	2.4E+00
1.0E+06	8.0E+05	1.3E+00	1.7E+00	1.8E+00	1.9E+00	1.9E+00	1.9E+00	1.9E+00	1.8E+00	1.7E+00
8.0E+05	7.0E+05	2.6E+00	3.2E+00	3.4E+00	3.5E+00	3.5E+00	3.5E+00	3.4E+00	3.4E+00	3.2E+00
7.0E+05	6.0E+05	1.3E-01	1.1E-01	1.0E-01	9.7E-02	9.6E-02	9.7E-02	9.9E-02	1.0E-01	1.1E-01
6.0E+05	5.1E+05	5.2E+00	9.0E+00	1.0E+01	1.1E+01	1.1E+01	1.1E+01	1.1E+01	1.0E+01	8.8E+00
5.1E+05	4.5E+05	1.2E-01	1.5E-01	1.6E-01	1.6E-01	1.6E-01	1.6E-01	1.6E-01	1.6E-01	1.5E-01
4.5E+05	4.0E+05	2.7E-02	4.3E-02	4.9E-02	5.1E-02	5.1E-02	5.1E-02	5.0E-02	4.8E-02	4.4E-02
4.0E+05	3.0E+05	5.1E-01	8.3E-01	9.4E-01	9.8E-01	1.0E+00	9.9E-01	9.6E-01	9.1E-01	8.2E-01
3.0E+05	2.0E+05	8.7E+00	1.3E+01	1.5E+01	1.6E+01	1.6E+01	1.6E+01	1.5E+01	1.5E+01	1.3E+01
2.0E+05	1.5E+05	1.7E+01	1.4E+01	1.3E+01	1.2E+01	1.2E+01	1.2E+01	1.2E+01	1.3E+01	1.4E+01
1.5E+05	1.2E+05	3.7E+00	3.0E+00	2.8E+00	2.7E+00	2.7E+00	2.7E+00	2.7E+00	2.8E+00	3.0E+00
1.2E+05	1.2E+05	1.2E-01	1.7E-01	1.9E-01	2.0E-01	2.0E-01	2.0E-01	1.9E-01	1.9E-01	1.7E-01
1.2E+05	1.0E+05	1.9E+00	1.5E+00	1.4E+00	1.3E+00	1.3E+00	1.3E+00	1.4E+00	1.4E+00	1.5E+00
1.0E+05	7.5E+04	2.6E+01	2.2E+01	2.0E+01	1.9E+01	1.9E+01	1.9E+01	2.0E+01	2.0E+01	2.2E+01
7.5E+04	6.0E+04	1.8E+01	1.4E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.4E+01	1.5E+01
6.0E+04	4.5E+04	2.8E+00	2.3E+00	2.1E+00	2.0E+00	2.0E+00	2.0E+00	2.1E+00	2.1E+00	2.3E+00
4.5E+04	3.0E+04	1.7E-01	2.7E-01	3.0E-01	3.1E-01	3.2E-01	3.1E-01	3.1E-01	2.9E-01	2.6E-01
3.0E+04	2.0E+04	3.8E+00	3.1E+00	2.9E+00	2.8E+00	2.7E+00	2.8E+00	2.8E+00	2.9E+00	3.2E+00
2.0E+04	1.5E+04	2.0E-02	1.6E-02	1.5E-02	1.4E-02	1.4E-02	1.4E-02	1.5E-02	1.5E-02	1.6E-02
1.5E+04	0.0E+00	3.1E-04	2.5E-04	2.3E-04	2.2E-04	2.2E-04	2.2E-04	2.3E-04	2.5E-04	2.8E-04
γ/s/metric tons U		2.83E+09	3.47E+09	3.76E+09	3.89E+09	3.94E+09	3.90E+09	3.82E+09	3.68E+09	3.43E+09

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3.0E+06	2.5E+06	1.1E+01	1.5E+01	1.6E+01	1.7E+01	1.7E+01	1.7E+01	1.7E+01	1.6E+01	1.5E+01
2.5E+06	2.0E+06	2.5E-07	1.5E-06	3.7E-06	6.8E-06	1.4E-05	3.1E-05	5.7E-05	1.4E-04	4.3E-04
2.0E+06	1.7E+06	2.8E-01	2.4E-01	2.3E-01	2.3E-01	2.3E-01	2.3E-01	2.3E-01	2.4E-01	2.4E-01
1.7E+06	1.5E+06	6.0E-01	8.0E-01	8.5E-01	8.7E-01	8.8E-01	8.7E-01	8.6E-01	8.4E-01	7.9E-01
1.5E+06	1.3E+06	5.3E-02	3.6E-02	3.1E-02	3.0E-02	2.9E-02	3.0E-02	3.1E-02	3.3E-02	3.7E-02
1.3E+06	1.0E+06	2.2E+00	1.6E+00	1.5E+00	1.4E+00	1.4E+00	1.4E+00	1.5E+00	1.5E+00	1.7E+00
1.0E+06	8.0E+05	2.0E+00	2.5E+00	2.6E+00	2.7E+00	2.7E+00	2.7E+00	2.6E+00	2.6E+00	2.5E+00
8.0E+05	7.0E+05	3.6E+00	4.3E+00	4.5E+00	4.6E+00	4.6E+00	4.6E+00	4.6E+00	4.5E+00	4.3E+00
7.0E+05	6.0E+05	9.7E-02	6.9E-02	6.2E-02	6.0E-02	5.9E-02	6.0E-02	6.1E-02	6.5E-02	7.3E-02
6.0E+05	5.1E+05	1.1E+01	1.6E+01	1.8E+01	1.8E+01	1.8E+01	1.8E+01	1.8E+01	1.7E+01	1.6E+01
5.1E+05	4.5E+05	1.7E-01	2.0E-01	2.1E-01	2.1E-01	2.2E-01	2.1E-01	2.1E-01	2.1E-01	2.0E-01
4.5E+05	4.0E+05	5.3E-02	7.3E-02	7.8E-02	8.0E-02	8.1E-02	8.0E-02	7.9E-02	7.7E-02	7.3E-02
4.0E+05	3.0E+05	1.0E+00	1.5E+00	1.6E+00	1.6E+00	1.6E+00	1.6E+00	1.6E+00	1.5E+00	1.4E+00
3.0E+05	2.0E+05	1.6E+01	2.2E+01	2.4E+01	2.4E+01	2.5E+01	2.4E+01	2.4E+01	2.3E+01	2.2E+01
2.0E+05	1.5E+05	1.0E+01	6.9E+00	6.0E+00	5.7E+00	5.6E+00	5.7E+00	5.8E+00	6.2E+00	7.1E+00
1.5E+05	1.2E+05	2.5E+00	1.7E+00	1.5E+00	1.4E+00	1.4E+00	1.4E+00	1.4E+00	1.5E+00	1.7E+00
1.2E+05	1.2E+05	2.0E-01	2.7E-01	2.9E-01	2.9E-01	3.0E-01	2.9E-01	2.9E-01	2.8E-01	2.7E-01
1.2E+05	1.0E+05	1.3E+00	8.7E-01	7.5E-01	7.1E-01	7.0E-01	7.1E-01	7.3E-01	7.9E-01	8.9E-01
1.0E+05	7.5E+04	1.9E+01	1.3E+01	1.1E+01	1.1E+01	1.1E+01	1.1E+01	1.1E+01	1.2E+01	1.3E+01
7.5E+04	6.0E+04	1.3E+01	8.4E+00	7.3E+00	6.9E+00	6.8E+00	6.9E+00	7.1E+00	7.6E+00	8.6E+00
6.0E+04	4.5E+04	2.5E+00	1.7E+00	1.4E+00	1.4E+00	1.3E+00	1.4E+00	1.4E+00	1.5E+00	1.7E+00
4.5E+04	3.0E+04	3.3E-01	4.5E-01	4.8E-01	4.9E-01	4.9E-01	4.9E-01	4.9E-01	4.7E-01	4.4E-01
3.0E+04	2.0E+04	2.4E+00	1.6E+00	1.4E+00	1.3E+00	1.3E+00	1.3E+00	1.3E+00	1.4E+00	1.6E+00
2.0E+04	1.5E+04	1.2E-02	8.1E-03	7.0E-03	6.6E-03	6.5E-03	6.6E-03	6.8E-03	7.3E-03	8.3E-03
1.5E+04	0.0E+00	1.9E-04	1.3E-04	1.1E-04	1.0E-04	1.0E-04	1.0E-04	1.1E-04	1.2E-04	1.4E-04
γ/s/metric tons U		3.9E+09	5.9E+09	6.8E+09	7.2E+09	7.4E+09	7.2E+09	7.0E+09	6.6E+09	5.8E+09

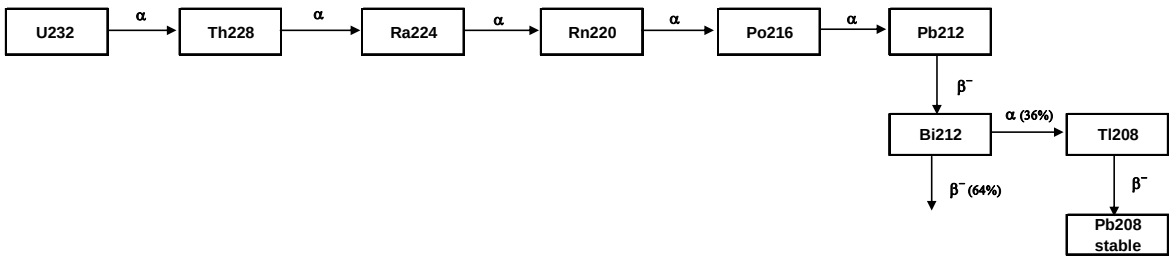

FIG. 2. Decay chain of 232U.

One notes a strong contribution to the γ radiations in the range of energy 2.5 MeV-3 MeV which will require significant biological protections for the interim storage, the transportation and the handling of reprocessed uranium. The maximum gamma radiation is reached after 10 years cooling of uranium after reprocessing. This component is due to the disintegrations of ^{208}Tl (half-life: 3.05 minutes) formed by successive decays of ^{232}U (half-live: 69 years).

3. The recycling of reprocessed uranium

The recycling of RepU in a PWR, in the form of UOX fuel, requires over-enriching in ^{235}U because of the presence of ^{234}U and ^{236}U isotopes. Because of the different selectivity of the individual enrichment methods for the different uranium isotopes, the level of the ^{235}U enrichment depends on the process used to enrich the uranium. For the first recycling of reprocessed uranium, Table 4 gives the enrichment in ^{235}U necessary to reach a burnup rate of 55 GW•d/t HM in a PWR and it gives the ratio of Separative Work Units (SWU), compared to an enrichment of natural uranium (reference). With natural uranium, this enrichment would be 4.5% ^{235}U; the tails assay is 0.25% ^{235}U.

With the ultracentrifugation (UCG) enrichment process, the current limit of 5% ^{235}U is quickly reached. Because of its high selectivity concerning ^{235}U, the Atomic Vapor Laser Isotope Separation (AVLIS) process allows to push back this limit. A gain in SWU ranging from 9% to 17% is limited to the case of enrichment of the RepU resulting from a fuel with 33 GW•d/t HM (see Table 4).

TABLE 4. ENRICHMENT OF ERU FUEL AND NEEDED SWU TO REACH 55 GW•d/t HM IN A PWR

Enrichment Process		**Origin of RepU**	
		UO_2; 33 GW•d/t HM; cooled 10 years	**UO2; 55 GW•d/t HM; cooled 10 years**
UCG	^{235}U	4.92%	5.17%
	SWU/SWU ref	0.91	1.16
AVLIS	^{235}U	4.64%	4.72%
	SWU/SWU ref	0.83	1.00

Enrichment in ^{235}U of the reprocessed uranium involves an enrichment of the other uranium isotopes whose level depends on the selected enrichment process. In case of ultracentrifugation, besides ^{235}U also ^{232}U, ^{234}U and ^{236}U are enriched to a certain extent. In case of AVLIS, the latter three isotopes are enriched to a much smaller extent. Table 5 gives the levels of enrichments (for ultracentrifugation (UCG) and laser enrichment (AVLIS)) of the uranium isotopes corresponding to the enrichments in ^{235}U of Table 4.

TABLE 5. ISOTOPIC ENRICHMENT OF REPU TO REACH 55 GW•d/t HM IN A PWR

Enrich. Process	Origin of RepU	^{232}U (%)	^{234}U (%)	^{235}U (%)	^{236}U (%)
UCG	UO_2; 33 GW•d/t HM; cooled 10 years	1.5 E-6	1.42 E-1	4.92	1.57
	UO_2; 55 GW•d/t HM; cooled 10 years	5.8 E-6	2.10 E-1	5.17	3.00
AVLIS*	UO_2; 33 GW•d/t HM; cooled 10 years	1.5 E-7	1.04 E-1	4.64	4.21E-1
	UO_2; 55 GW•d/t HM; cooled 10 years	4.7 E-7	1.48 E-1	4.72	6.75E-1

* Assumptions on the theoretical ionization selectivity: S_{U232} = infinite, S_{U234} = 1, S_{U236} = 100.

It should be noted that, in the case of enrichment by UCG, a significant increase in the composition of the even isotopes and in particular of ^{232}U (~ a factor of 10 compared to the RepU before recycling) appears which will involve an increase in the biological shielding for the transportation and the handling of this uranium during operations of fuel fabrication. The depleted uranium resulting from UCG enrichment will also contain ^{232}U.

4. Impact of the recycling of the reprocessed uranium on the actinides production

The recycling of the RepU will involve a modification of the production of actinides under irradiation compared to a standard UO_2 fuel. Table 6 gives the composition of these actinides for a burnup rate of 55 GW•d/t HM and a cooling time of 10 years. Table 7 gives the isotopic compositions of the actinides.

4.1. The uranium

The ^{235}U content of unloaded spent ERU fuel lies between 0.9% and 1.2%, according to the origin of the uranium and the enrichment process. With a ^{235}U contents higher than that of standard RepU derived from spent ENU fuel (0.8% ^{235}U), but with the ^{236}U content, higher from a going factor from 1.4 to 4.4 compared to that of a standard RepU, the material gained from the reprocessing of spent ERU fuel will require significant over-enrichment in ^{235}U for the second recycling under the same conditions, meaning higher than 6% ^{235}U with the UCG process and about 5% ^{235}U with AVLIS.

4.2. The neptunium

The production of neptunium increases significantly, until a factor of 4, compared to the production in a standard UO_2 fuel. This is due to the higher initial ^{236}U concentration in irradiated ERU fuel at the origin of the formation of ^{237}Np (neutron capture of ^{236}U creates ^{237}U which has a half-life of 7 days and thus quickly decays to ^{237}Np).

4.3. The plutonium

The production of plutonium increases by 5% to 10% compared to a standard UO_2 fuel with a strong increase in the concentration of ^{238}Pu (until a factor of 3). This is due to the highest production of ^{237}Np at the origin of the formation of ^{238}Pu under neutron flux. This increase will have an impact on the thermal power of plutonium in the MOX fuel fabrication processes, as ^{238}Pu is strongly contributing to this thermal power by its α decay. The quality of fissile plutonium is impacted to a smaller extent; the composition in ^{242}Pu drops between 10% and 30% due to a slight decrease of the ^{240}Pu production.

4.4. The americium

The production of americium, in quantity and isotopic composition, is approximately the same one as in a UO_2 standard fuel.

4.5. The curium

One notes a fall of the production of curium in irradiated ERU fuel, between 10% and 30%, compared to the production of curium in a standard ENU fuel. Curium is formed mainly by successive neutron captures and beta decays of ^{242}Pu in a UO_2 fuel.

4. The potential gain in natural uranium

On a park of PWRs loaded with UO_2 fuels, one discharges each year 93% of initial enriched uranium which can be re-used after enrichment in ^{235}U with the content necessary to reach a burnup rate of 55 GW•d/t HM. Under these conditions, the recycling of this reprocessed uranium makes it possible to save approximately 10% of natural uranium and about 1.6% of SWU.

The gains are even much higher if one adds those obtained with the recycling of plutonium.

5. Conclusion

Studies on reprocessed uranium recycling in PWRs show that:

- The enrichment of RepU by the industrial UCG process is a benefit solution (profit in enrichment) for the reprocessed uranium issued from the standard UO2 fuel having reached a burnup rate of about 33 GW•d/t HM.
- For the burnup rates higher than those usually considered, or for multiple recycling, enrichment by non-selective technologies, like UCG, is not profitable (loss in enrichment). Reprocessing of corresponding irradiated fuel poses problems with the current processes, because of the very high ^{238}Pu contents.
- The presence of ^{232}U in the reprocessed uranium needs a detailed attention during the different operations in the front end cycle.
- The selective enrichment processes as AVLIS are profitable (profit in enrichment) for all the burnup rates and the multi recycling considered

TABLE 6. MASS COMPOSITION (%) OF ACTINIDES FOR OF SPENT ERU FUEL AND STANDARD UO_2 (ENU) FUEL (55 GW•d/t HM; cooled 10 years)

Actinide	**ERU FUEL**				**STANDARD UO_2 (ENU)**
	Origin: 33 GW•d/t HM; cooled 10 years		**Origin: 55 GW•d/t HM; cooled 10 years**		
	Enrichment Process				
	UCG	**AVLIS**	**UCG**	**AVLIS**	**UCG**
U	9.28E+01	9.29E+01	9.26E+01	9.29E+01	9.30E+01
Np	1.93E-01	9.48E-02	3.12E-01	1.17E-01	7.80E-02
Pu	1.23E+00	1.21E+00	1.26E+00	1.21E+00	1.16E+00
Am	9.77E-02	1.03E-01	9.29E-02	1.01E-01	1.01E-01
Cm	6.92E-03	8.18E-03	5.87E-03	7.75E-03	8.76E-03

TABLE 7. ISOTOPIC COMPOSITION (%) OF EACH ACTINIDE FOR SPENT ERU FUEL AND SPENT STANDARD UO2 (ENU) FUEL (55 GW•d/t HM; cooled 10 years)

Isotope	ERU FUEL				STANDARD UO_2 (ENU)
	Origin: 33 GW•d/t HM; cooled 10 years		Origin: 55 GW•d/t HM; cooled 10 years		
	Enrichment Process				
	UCG	AVLIS	UCG	AVLIS	UCG
^{232}U	1.9E-06	8.0E-07	4.2E-06	1.2E-06	4.7E-07
^{234}U	8.5E-02	5.8E-02	1.3E-01	8.3E-02	2.5E-02
^{235}U	1.0E+00	9.0E-01	1.2E+00	9.4E-01	7.9E-01
^{236}U	2.2E+00	1.1E+00	3.5E+00	1.3E+00	6.4E-01
^{238}U	9.7E+01	9.8E+01	9.5E+01	9.8E+01	9.9E+01
^{238}Pu	7.5E+00	4.0E+00	1.1E+01	4.8E+00	3.4E+00
^{239}Pu	5.2E+01	5.4E+01	5.1E+01	5.3E+01	5.3E+01
^{240}Pu	2.4E+01	2.5E+01	2.3E+01	2.5E+01	2.6E+01
^{241}Pu	9.2E+00	9.7E+00	8.7E+00	9.6E+00	9.8E+00
^{242}Pu	6.9E+00	7.6E+00	6.2E+00	7.4E+00	8.4E+00
^{214}Am	7.9E+01	7.7E+01	8.0E+01	7.8E+01	7.6E+01
^{243}Am	2.2E+01	2.0E+01	2.2E+01	2.1E+01	2.4E+01
^{244}Cm	8.9E+01	8.8E+01	8.9E+01	8.8E+01	8.9E+01
^{245}Cm	9.3E+00	9.5E+00	9.1E+00	9.4E+00	9.1E+00
^{246}Cm	1.1E+00	1.2E+00	1.0E+00	1.2E+00	1.3E+00

Utilization of reprocessed uranium in Indian reactors

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Abstract. The closed fuel cycle option with the reprocessing and recycling of uranium and plutonium allows better utilisation of the uranium resources. This fact is getting greater significance in the context of India's nuclear power programme due to its limited uranium and vast thorium resources. The recycling of uranium in thermal reactors has been driven by two factors: Firstly, it does not call for significant changes in the thermal reactor fuel cycle facilities. Secondly, it will not affect the recycling in fast reactors in the future. This paper highlights India's perception about uranium recycling, its experience, and its future programmes.

1. Introduction [1, 2]

The concept of reprocessing and recycling has been to a large extent driven by economic, strategic, and political factors. Fast reactors are the ideal platform for the recycling of uranium and plutonium. However, the recycling of uranium and plutonium in thermal reactors on a small scale has taken precedence over the recycling in fast reactors.

The somewhat unique current fuel resource position of India makes the adoption of the closed fuel cycle a necessary as well as a superior option. India has a modest reserve of uranium, but an abundant source of thorium. A three-stage power programme has been devised to utilise effectively the limited uranium resource and the large thorium resource. Figure 1 gives an overview of India's three-stage power programme. The first stage involves the utilisation of natural uranium in pressurized heavy water reactors (PHWR). The second stage involves the utilisation of plutonium obtained from reprocessing the spent PHWR fuel in fast reactors. The third stage involves the Th-^{233}U-cycle based reactor system.

It must be noted that the aforementioned strategy is essential for ensuring an optimum utilisation of nuclear fuel resources and to cater a sustainable rate of growth of nuclear power in the global context. As mentioned above, in case of India, the priority is for adopting this strategy at an earlier date. In August 2007, fifteen PHWRs and two boiling water reactors (BWR) with a total capacity of 4120 MW(e) were under operation in India. In addition, three PHWRs and two water-cooled and water-moderated reactors (VVER) with a total capacity of 2660 MW(e) were under construction. India's installed nuclear generating capacity is planned to increase to more than 20 GW(e) in the next decade through a mixed addition of PHWRs, Light Water Reactors (LWR), fast breeder reactors (FBR) and advanced heavy water reactors (AHWR). The recycling of uranium and plutonium will have an important role in achieving the projected growth in nuclear power.

The following sections highlight the various programmes that have been implemented as well as those which are being planned with regard to the use of reprocessed uranium (RepU) in India.

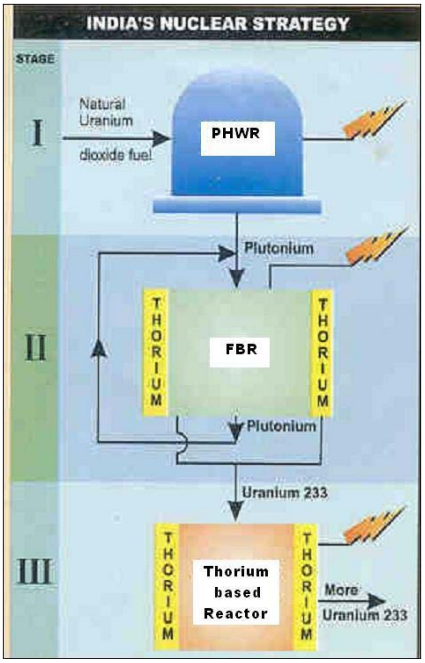

FIG. 1. India's three-stage nuclear power programme.

2. Reprocessing in India [3, 4]

The spent fuel reprocessing activity in India is almost four decades old. The experience in spent fuel reprocessing based on the PUREX (plutonium and uranium recovery by extraction) process has given the confidence that this technology can be successfully employed for the recovery of both uranium and plutonium with a yield exceeding 99.5%. It began with the commissioning of the Trombay Plutonium Plant in 1964 for the reprocessing the aluminium clad metallic uranium spent fuel from the research reactors. For power reactor spent fuel, two plants are at present under operation to reprocess the zirconium clad uranium dioxide fuel from PHWRs. The reprocessing capacity will be further enhanced to meet the recycling requirements of India's power programme.

3. Characteristics of Indian RepU [5, 6]

Natural uranium consists of the isotopes of ^{235U} and ^{238}U, together with small quantities of ^{234}U. During irradiation, other uranium isotopes like ^{223}U and ^{236}U along with a wide range of fission products and minor actinides are generated. These fission products and the transuranics are separated from uranium during the reprocessing and their concentrations are kept to low levels by employing high decontamination factors. The concentration of isotopes of uranium discharged after reprocessing, however, depends upon the type of reactor, the fuel burnup in the reactor, the cooling period of the fuel prior to reprocessing and the ageing time.

The difference in the concentration of uranium isotopes of RepU from that of natural uranium has a profound influence on two of the properties. RepU has a higher neutron absorption in the thermal reactor spectrum and a greater radiological activity. The nuclear design must take into account the neutron absorption effect of ^{236}U by increasing the fissile enrichment. As a rule of thumb, the effect will require deduction of about 0.3% ^{235}U for every 1% ^{236}U. There are both external and internal dose implications during the manufacturing and handling of RepU fuel. The internal dose implications of RepU are due to its slightly higher specific activity as a result of higher ^{234}U concentration. The major contribution to the external whole body dose will be due to □emission from ^{208}Tl, which is a daughter product of ^{232}U. Multiple recycling will increase the concentration of ^{232}U and ^{234}U, which will result in higher dose levels during fuel manufacturing. The tail assays from the enrichment plants using RepU have much greater health physics connotations. This will particularly have to be taken into account during the usage of the depleted uranium (tails) obtained from the enrichment of RepU [7].

The recycling of uranium in LWRs worldwide has involved the reprocessing of fuel with an average burnup of about 30 000-35 000 MW•d/t HM. The uranyl nitrate obtained from the reprocessing plant is converted to UF_6 for re-enrichment in ^{235}U. After enrichment the UF_6 is converted to uranium oxide for use in LWRs. The uranium recycle scheme in India differs in the following ways from that practised in most other countries:

- PHWRs use natural uranium (0.7% ^{235}U), unlike LWRs which use low enriched uranium (LEU) (3-4% ^{235}U).
- The average burnup in PHWRs is low and is only about 6700 MW•d/t HM.
- The uranyl nitrate solution is directly converted to uranium oxide and there is no re-enrichment process carried out.

There is, therefore, a direct utilisation of RepU with a depleted fissile isotope content (i.e. ^{235}U is depleted and is lower than 0.7%). The application of RepU in India has, therefore, been in accordance with its fissile content. RepU has found application in flux flattening of initial PHWR cores, as a substitute for natural uranium to conserve the available limited uranium resources, as a fertile matrix and for breeding fissile material in fast reactors.

The concentration of the other uranium isotopes - ^{232}U, ^{234}U and ^{236}U - is also low. Hence, the RepU's radiation and neutronic characteristics are almost similar to those of natural uranium.

4. Utilization of RepU in Indian PHWRs [8, 9]

RepU fuel fabrication is carried out in the Nuclear Fuel Complex (NFC) at Hyderabad using the same facilities which fabricate the natural uranium fuel. The use of RepU has not required any major modifications in manufacturing, transport, storage, and other operations, which are affected by radiological considerations. The powder preparation is performed by the dry route as it minimises the generation of liquid effluents. The off-gases are passed through a water spray scrubber, then through high efficiency particulate air-filters (HEPA filters) before being let out through the stack. The derived air concentration (DAC) that is a measure of the contamination of the fission products and transuranics is kept to levels close to those of fresh uranium by employing high decontamination factors in reprocessing. In order to meet the DAC limits, the guideline on the amount of input radiological substances specified by the Indian Regulatory Agency (AERB) is as follows:

$$\frac{\text{(Microcurie of } \gamma \text{ emitting fission products per gram of U)}}{0.2} + \frac{\text{(Microgram of Pu per gram of U)}}{0.3} < 1.0$$

One of the most important precautions taken during handling is to maintain identity of the material and avoid any mixup with natural uranium. The presence of small quantities of radionuclides such as ^{90}Sr, ^{106}Ru and ^{137}Cs which are beta emitters has required a few other special steps like the following:

- The air activity is controlled by providing a secondary ventilation system in addition to the primary system.
- The powder transfer room is maintained under negative pressure with respect to the atmosphere.
- NFC introduced the concept of container handling for the fuel material and using the vacuum charging system for transferring from containers to the calcination bunkers.

The utilisation of RepU in PHWRs, however, required detailed reactor physics studies to be carried out before loading into reactors. The initial core starting with all fresh fuel will have an unacceptably high power in the central region, unless some means of flux flattening in the absence of differential burnup is provided. The utilisation of RepU minimises the time between initial criticality and attainment of full power. Table 1 gives details of the RepU loaded in PHWRs for initial core flux flattening.

TABLE 1. REPU LOADING IN VARIOUS PHWRs

Year of Criticality	Reactor	Number of RepU Fuel Bundles	Quantity of Uranium Oxide (t)
1980	RAPS-2	656	9.8
1983	MAPS-1	656	9.8
1985	MAPS-2	384	5.7
1989	NAPS-1	384	5.7
1991	NAPS-2	384	5.7
	MAPS-1[1)]	1520	22.7
	MAPS-2[1)]	1516	22.6
2005	TAPS-3	3872	96.8
2006	TAPS-4	2208	55.2
2007	KGS-3	2388	35.7

[1)] After re-tubing

RepU has also been loaded in the equilibrium cores of PHWRs to conserve natural uranium resources. Detailed Post Irradiation Examination (PIE) have also been carried out on a few bundles used in MAPS-1. The bundles had operated for a burnup of about 4700 MW•d/t HM and a peak linear heat rating of 48kW/m. The examination did not reveal any difference in the performance of RepU fuel from that of the natural uranium fuel [10].

5. Use of Rep U for high burnup fuel in PHWRs [11, 12]

Studies have been carried out for the use of RepU mixed with plutonium as high burnup fuel for PHWRs. The advantage of using RepU is that it can accommodate higher enrichments of plutonium. Two schemes have been studied for the 220 MW(e) PHWRs, which employs the 19-element fuel bundle. In one scheme, the central 7 fuel pins will have MOX fuel and the outer 12 fuel pins will have natural uranium oxide. In the other scheme all the fuel pins will have MOX fuel, but with the outer 12 fuel pins having a lower plutonium enrichment.

Studies have also been carried out for the recycling of uranium from the spent fuel of the two operating BWRs into PHWRs. The ^{235}U levels in the discharged fuel will be slightly higher than those in natural uranium and this will aid in increasing the burnup of PHWR fuel.

6. Recycling in fast reactors [13]

The fast reactor programme will be utilising the RepU on a large scale. In India, a fast breeder test reactor (FBTR) is currently under operation and a 500 MW(e) prototype fast breeder reactor (PFBR) is under construction and will begin operation in 2011. The reactor core of the PFBR will consist of fuel sub-assemblies and blanket sub-assemblies. The fuel sub-assemblies will have RepU as fertile matrix mixed with 20% and 30% plutonium. The blanket sub-assemblies will have RepU for breeding plutonium.

RepU fuel pellets for the initial core axial blanket of the PFBR have been fabricated by the conventional powder-pellet route inside glove boxes. The major fabrication steps involved are the mixing of the binder and the lubricant with the RepU powder, the pre-compaction and granulation using a rotary press and an oscillatory granulator, the final compaction using a rotary press and sintering at 1650 ºC in a special environment (nitrogen + 7% hydrogen).

7. Conclusion

Recycling of uranium has an important place in India’s nuclear power programme, in particular due to its slightly unique fuel resource position. India's power programme is at present primarily based on PHWRs, which employs natural uranium as fuel. Fast reactors will have a very important role in

meeting the energy requirements of India and recycling is an essential component in the fast reactor programme. The recycling of uranium will be on a very large scale in fast reactors and on a smaller scale in PHWRs.

The scenario of uranium recycling in PHWRs is different from that in most other countries which employ LWRs with LEU as fuel. The lower burnups in PHWRs provide an inherent advantage in terms of radiological consequences. The annual discharge of spent fuel from PHWRs is about 150 t per GW(e) and year. The uranium recycling programme will be increasing considerably in the next few decades for the projected increase in nuclear generation capacity.

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Technical feasibility of the use of RU-43 fuel in CANDU-6 reactors of the Cernavoda NPP

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Abstract. Reprocessed uranium (RepU) is a by-product of many Light Water Reactor (LWR) fuel reprocessing programs. A fissile content of 0.9 to 1.0 w/o ^{235}U in the RepU makes it impossible for direct reuse in an LWR without prior re-enrichment, but CANDU reactors have a sufficiently high neutron economy to use RepU as fuel. The Institute for Nuclear Research (INR) Pitesti has analyzed the feasibility of using RepU fuel with 0.9-1.1w/o ^{235}U in the CANDU-6 reactors of the Cernavoda Nuclear Power Plant (Cernavoda NPP). Using RepU fuel would produce a significant increase in the fuel discharge burnup, from 170 MW•h/kg U currently achieved with natural uranium (Unat) fuel to about 355 MW•h/kg U. This would lead to reduced fuel cycle costs and a large reduction in the spent fuel volume per full power year of operation. The RepU fuel bundle design known as RU-43 is being developed by INR Pitesti and is now at the stage of final design verification. Early work has concentrated on RU-43 fuel bundle design optimization, safety and reactor physics assessment. The changes in fuel element (rod) and fuel bundle design contribute to the many advantages offered by the RU-43 bundle. Verification of the design of the RU-43 fuel bundle is performed in a way that shows that design criteria are met and it is mostly covered by proof tests, such as flow and irradiation tests. The most relevant calculations performed on this fuel bundle design version are presented in this paper. Also, the stages of an experimental program aiming to verify the operating performance are briefly described.

1. Introduction

More than 50 000 fuel bundles containing natural uranium fuel have been irradiated in the CANDU-6 reactors of Romania's Cernavoda NPP, with a very low defect rate, to a core-average discharge burnup of 170-190 MW•h/kg U.

A unique feature of the CANDU reactor design is its ability to use alternative fuel cycles other than natural uranium (Unat), without requiring major modifications of the basic reactor design. These alternative fuel cycles, which are known as advanced fuel cycles, utilize a variety of fissile materials, including Slightly Enriched Uranium (SEU) from enrichment facilities, and reprocessed uranium (RepU) obtained from the reprocessing of the spent fuel of light water reactors (LWR).

RepU is a by-product of many LWR fuel recycling programs. After fission products and plutonium (Pu) have been removed from spent LWR fuel, RepU is left. A fissile content in the RepU of 0.9 to 1.1 w/o ^{235}U makes it impossible for direct reuse in an LWR without prior re-enrichment. But CANDU reactors have a sufficiently high neutron economy to use RepU as fuel. RepU from spent LWR fuel can be considered as a lower cost source of enrichment at the optimal enrichment level for CANDU fuel pellets. In Europe the feedstock of RepU is approaching several thousand tonnes and would provide sufficient fuel for a few hundred CANDU-6 reactor years of operation.

The use of RepU fuel offers significant benefits to CANDU reactor operators. RepU fuel improves the fuel cycle economics by increasing the fuel burnup, which enables large cost reductions in fuel consumption and in spent fuel disposal. RepU fuel offers enhanced operating margins that can be applied to increase the reactor power. These benefits can be realized using existing fuel production technologies and practices, and with almost negligible changes to fuel receipt and handling procedures at the reactor. The application of RepU fuel could be an important element in the Cernavoda NPP. For

this reason the Institute for Nuclear Research at Pitesti (INR Pitesti) has started a research programme aiming at the development of a new fuel bundle for extended burnup operations referred to as RU-43.

The changes in fuel rod and fuel bundle design contribute to the many advantages offered by the RU-43 bundle. Verification of the design of the RU-43 fuel bundle is performed in a way that shows that design criteria are met, and is mostly covered by proof tests, such as flow and irradiation tests. However, some design parameters are verified by analyses rather than by experiments because appropriate experimental simulations are unavailable in INR Pitesti or because they take a long time to provide results.

The most relevant calculations performed on this fuel bundle design version are presented. Also, the stages of an experimental program aiming at the verification of the operating performance are briefly described in this paper.

2. Fuel bundle design

In order to meet extended burnup with SEU fuel in CANDU reactors, one of the possibilities is a more sub-divided bundle design. The actual version of RepU fuel design (RU-43 fuel bundle) is the result of a long process of analyses and improvements, in which successive preliminary design versions have been evaluated [1, 2]. A step-by-step strategy was adopted, in which every new step is based on the complete utilization of the results obtained in the preceding steps.

The RU-43 design is a 43-rod fuel assembly offering improved operating and safety margins, compared with the standard natural uranium (Unat) CANDU-6 bundle with 37 rods for operating CANDU-6 reactors referred to as NU-37. The RU-43 bundle consist of two fuel rod sizes: small diameter rods in the outer and intermediate rings, and larger diameters rods in the inner and centre rings. The small diameter rods (thirty five rods with 11.5 mm diameter each) in the two outer rings allow the peak rod ratings in the bundle to be reduced by 20% in comparison to the standard NU-37 bundle. The larger diameter rods (eight rods with 13.5 mm diameter each) in the inner rings of the bundle compensate the fuel volume lost due to the smaller diameter outer ring rods. The isotopic specification of RepU fuel is very similar to that of SEU fuel, but with higher concentrations of ^{234}U and ^{236}U than the concentration found in enriched fuel derived directly from Unat. To maintain compatibility of the new bundle with the existing CANDU-6 reactor systems, the basic overall dimensions of the RU-43 fuel bundle were designed to be the same as those of the NU-37 bundle. The detailed design features of the bundle have continued to evolve as a result of ongoing design analyses and thermal hydraulic testing.

The pellet shape (dish depth, chamfer angle and width, land width), CANLUB thickness, and other features are based on both analyses and irradiation experience in the TRIGA Material Testing (MT) reactor of the INR Pitesti. The internal rod design provides internal volume to accommodate fission gas pressure and also minimizes inter-pellet sheath strains. The end cap-to-sheath weld has been designed to avoid any sharp notches and associated stresses at the internal weld-upset region. The sheath thickness is thin to reduce neutron absorption and is designed to prevent longitudinal ridge formation and axial collapse due to the coolant pressure and temperature in the reactor. The sheath may collapse onto the pellets under high coolant pressures. This event coupled with the thermal expansion of pellet might lead to promote good heat transfer, which in-turn lowers pellet centre-line temperatures and decreases fission gas release. At the same time, excessive sheath collapse (either axially or circumferentially) that could lead to higher strains and cracking is avoided. The fuel bundle, in all other respects, is designed to be equivalent to the NU-37 bundle of all reactor systems. To verify this, preliminary tests were performed for pressure drop and bundle strength under a number of situations. The thermal hydraulic design characteristics of RU-43 fuel bundles in a CANDU-6 reactor have been studied by investigating comparisons of channel axial heat flux distribution (AFD) and bundle radial heat flux distribution (RFD) of RU-43 bundles in a CANDU-6 reactor, and then by evaluating the critical channel power.[3].

3. Neutronic calculation

The optimisation of the design from the neutronic point of view is here considered by means of cell and whole reactor calculations. INR Pitesti has performed fuel management calculations for the use of RU-43 fuel in a CANDU-6 reactor and established the power envelopes used in fuel performance analyses.

In the CANDU-6 reactors, an 8-bundle shift refuelling scheme is currently employed in natural uranium fuel management. This refuelling scheme leads to difficulties in the CANDU in-core fuel management if RU-43 fuel bundles are used because of the reactivity increase. Considering that the discharge burnup of the RU-43 fuel is almost twice that of the NU-37 fuel, a 4-bundle shift refueling scheme is preferable for the in-core fuel management of the RU-43 fuel in the CANDU-6 reactor.

The objective of the study was to evaluate the feasibility of a 4-bundle shift refuelling for a CANDU-6 equilibrium RU-43 core without any violation included in the zone control system. The computer codes used in this study were WIMS AECL with the ENDF/B-V nuclear data library [4] for the lattice cell calculation, PIJXYZ [4] for the super lattice cell calculation and the incremental cross section of the control devices and DIREN [4] for the fuelling simulation, the core flux/power calculation and for the selection of the refuelling channels.

A 1000 full power day (FPD) core follow simulation with RU-43 fuel has been completed [5]. Refuelling started at the 257th FPD. The reference fuelling scheme for RU-43 fuel bundles was a 4-bundle shift.

The first and most crucial result of the simulations is that the equilibrium core was able to be refuelled and maintained for 1000 FPDs without exceeding the channel power and bundle power limits, or causing uncontrollable tilts.

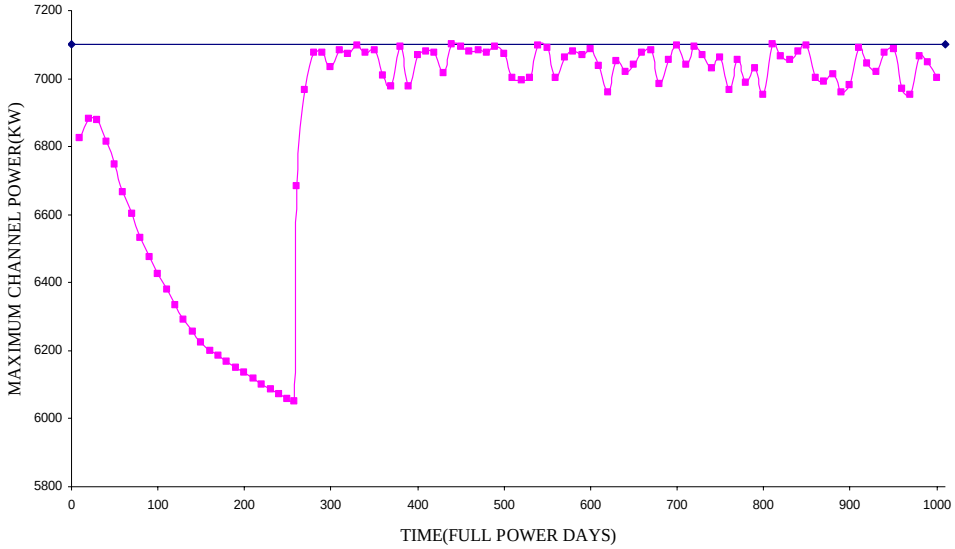

FIG. 1. Variation of maximum channel powers with time.

Figure 1 shows the variations of the maximum channel power (MCP) as the results of the 1000 FPDs equilibrium core simulation with the 4-bundle shift refuelling scheme. As shown in this Figure, the calculated highest maximum channel power is 6504 kW. It is found that the self-imposed operating limits of 7100 kW and 900 kW for the MCP and MBP (maximum bundle power) limits, respectively, were met throughout all the simulations using the 4-bundle shift refuelling scheme. Throughout this 1000 FDP refuelling simulation, it was found that the average discharge burnup was calculated to be about 355.2 MW•h/kg U (time average) and the refuelling rate to be about 3.1 channels per day.

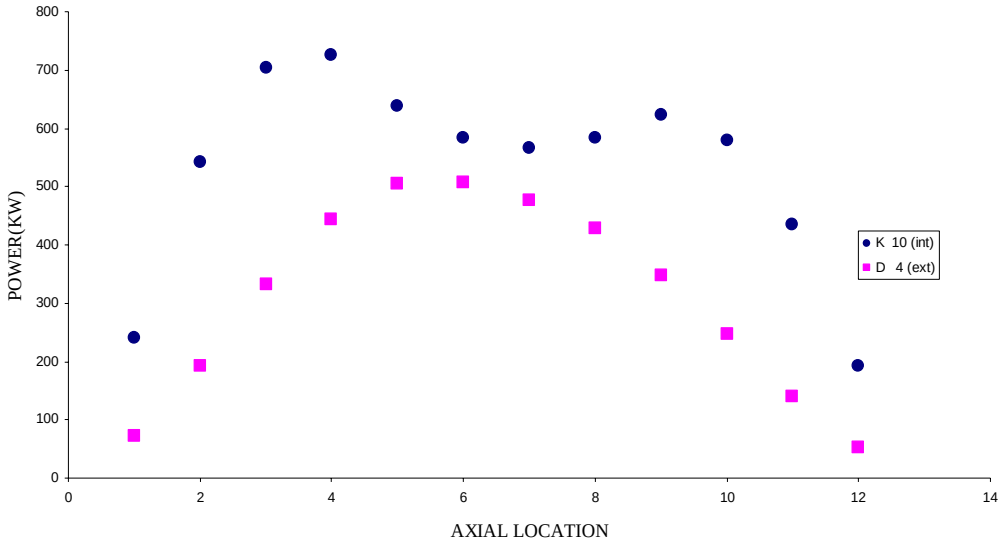

FIG. 2. Axial power distribution (time average data).

Also of interest is the axial power shape that results from the use of RU-43 fuel. Figure 2 shows the time average axial powers for a high power, inner core channel and a low power, outer core channel. The power peaking towards the inlet end has positive implications on the critical channel power values. Comparisons of other core follow results with time average results can be found in Table 1.

TABLE 1. COMPARISON OF TIME AVERAGE AND CORE FOLLOW VALUES

Item	**Time Average**	**Core Follow**
Exit Burnup [MW•h/kg]	355.2	345.6
Feed Rate [channels/FPD]	3.5	3.1
Feed Rate [bundles/FPD]	8.4	7.8
Maximum Channel Power [kW]	6504	7100
Ave. Max. Channel Power [kW]	6236	7050
Maximum Bundle Power [kW]	743	950

Figure 3 shows the linear rod powers plotted versus burnup for the ring-4 rods in the RU-43 fuel bundle for the entire simulation period of normal refuelling. The power boost envelopes for these fuel rods due to refuelling operations are shown in Fig. 4. Each dot on the graph represents the maximum linear rod power from a bundle. Every bundle that shows a power boost greater than 10 kW at any time in the core follow is represented. Curves of 1% defect probability are shown. For the fuel failure probability to exceed 1% both threshold curves must be exceeded.

The range of concern in Figure 4 is the burnup interval of 100 to 350 MW•h/kg U. Figure 3 clearly shows that the rods in this range do not come close to approaching the SCC rod power threshold limit. The large margin between the CANLUB rod power threshold and the bundle maximum linear rod powers suggests that, even with power boosts occurring at burnups between 100 and 350 MW•h/kg U caused by a 4-bundle shift, there is no fuel failure expected.

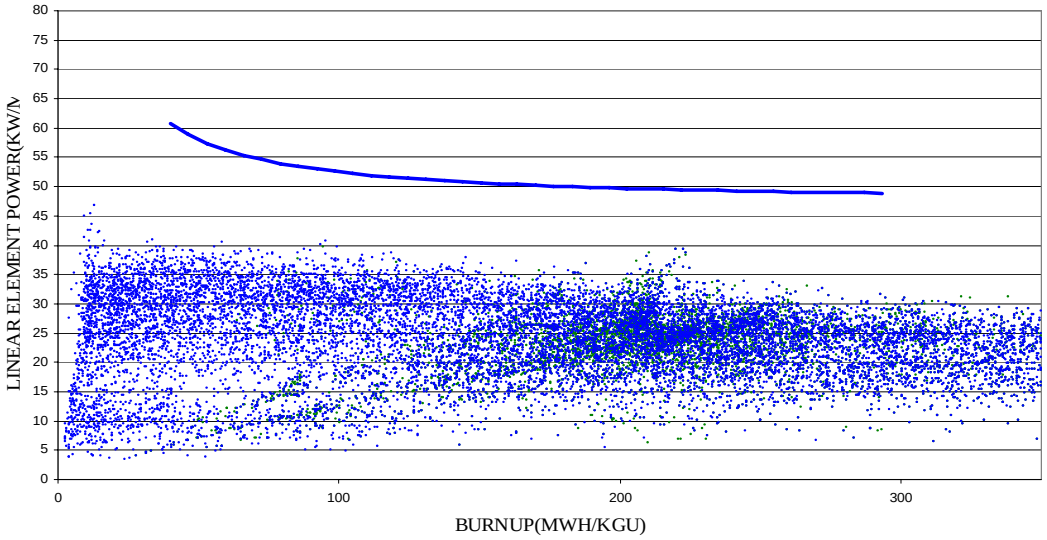

FIG. 3. Maximum linear rod powers in outer ring of RU-43 fuel using 4-bundle shift.

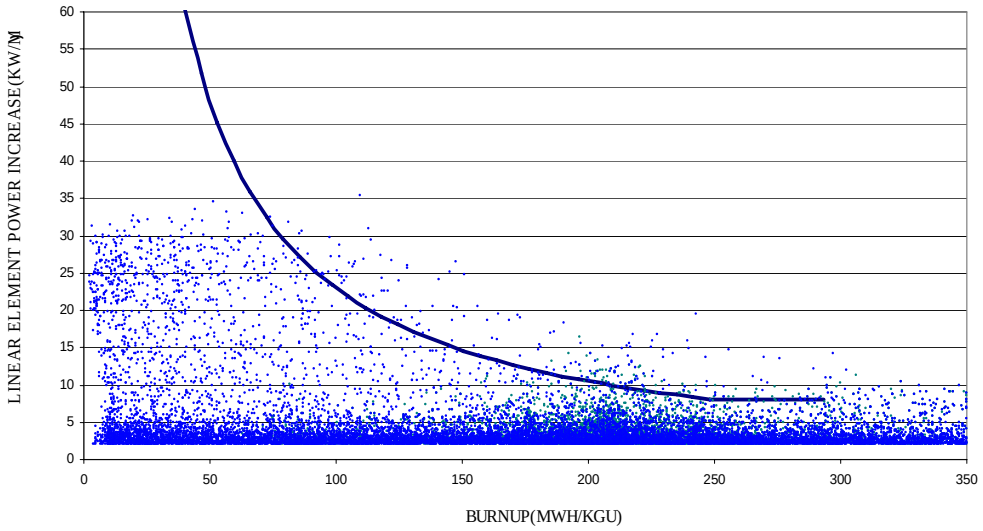

FIG.4. Linear rod power boosts in outer ring of RU-43 fuel using 4- bundle shift.

The results of the 1000 FPD core follow show that the peak linear rod ratings with the RU-43 bundle were bellow 48 kW/m. Power boosts during refuelling were 37 kW/m at a very low rod burnup of 48 MW•h/kg U and were decreasing with the burnup. The results of the core management confirm that RU-43 fuel bundles meet CANDU fuel performance criteria. They would not cause excessive channel or local overpowers, or significant risk of fuel rod failure. This applies in spite of its extended burnup and slight enrichment relative to natural uranium fuel.

Figure 5 shows the relative rod linear power in a bundle according to the bundle average burnup for RU-43. As shown in Fig. 5, the initial order of the relative rod linear power of outer, inner, center and intermediate ring is changed to the order of inner, outer, center and intermediate ring after a burnup of 130 MW•h/kg U.

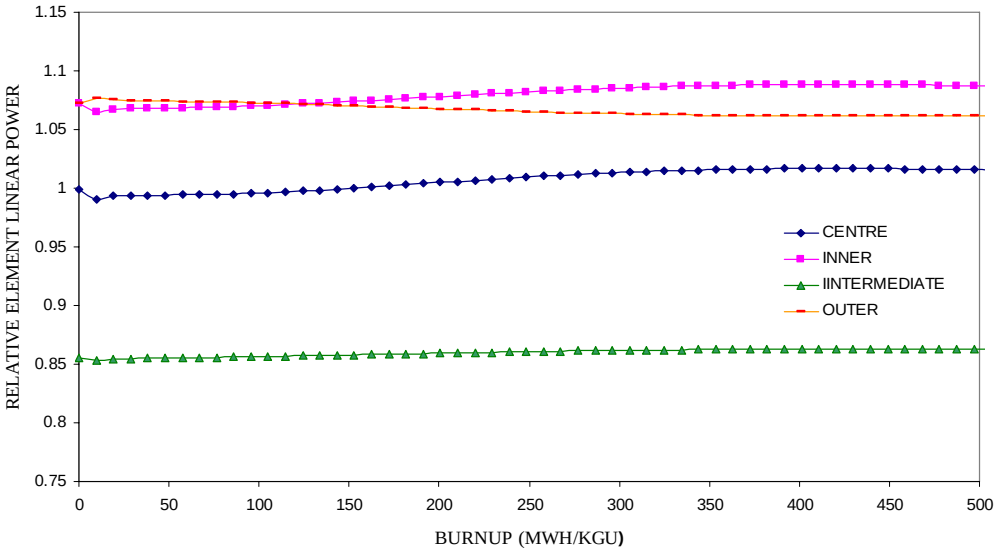

FIG. 5. Bundle radial power distribution.

The fuel rods of the outer ring have a maximum value at plutonium peak burnup (45 MW•h/kg U); above this level the power decreases (see Fig. 5). However, the fuel rods of the inner ring which have the highest power have the minimum at plutonium peak burnup and the maximum at discharge burnup.

The LEGENTR code models the CANDU fuel super cells in 3D rectangular geometry. These calculation results [6] show that, for the same operating conditions, the maximum rod linear power at the fuel end is lower in fresh RU-43 fuel than it is in fresh NU-37 fuel, because of the 43 rod design in RU-43 fuel.

The values of the void reactivity obtained with the CP2D and the Monte Carlo MCNP4C codes for cells with RU-43 fuel bundles are slightly lower than the results obtained for voided CANDU–6 cells with NU-37 bundles [7]. From this point of view the proposed RU-43 design shows a superior neutronic performance if compared with the NU-37 bundle which is currently used in the Cernavoda NPP.

4. Thermo-mechanical analyses

The changes in fuel rod and fuel bundle design contribute to the many advantages offered by the RU-43 bundle. The lower heat rating of the RU-43 fuel rods at current bundle powers leads to lower fuel temperatures. Hence less free fission gas inventory is produced under normal operating conditions compared with the free fission gas inventory produced in NU-37 fuel rods at a similar bundle power. The lower fuel rating in the RU-43 bundle facilitates the adoption of extended burnups in CANDU reactors that are necessary for the economic use of various attractive fuel cycles. Also, the lower fuel rating reduces the consequences of most design-basis accidents. RU-43 fuel is designed to have hydraulic and neutronic characteristics that are similar to those of the existing fuel. This feature allows the operators to introduce RU-43 bundles during normal on-power refuelling.

The combination of low peak rod ratings and a low and declining power boost envelope provide good confidence in the extended burnup fuel performance. Using the ROFEM code the RU-43 fuel rod performance under power envelopes was predicted as shown in Table 2 [8]. This prediction indicates that the RU-43 fuel with extended burnup will show as good in-reactor performance as standard CANDU fuel does, because the fuel temperature and the rod internal gas pressure are far below the design criteria. The plastic hoop strains of the sheath are within a reasonable range in terms of sheath plastic strain. The sheath strain and fission gas release predicted at end of life (EOL) with STP

condition are lower than those for a NU-37 bundle. Under severe combinations of design parameters the code predicts a little higher cladding strain, but this strain is still close to NU-37 bundle calculation results. The analysis results of thermally-induced bowing using the SIECC code during in-reactor service and refuelling indicate that for the RU-43 bundle the maximum bows are in the direction of the pressure tube wall and that they are close to those of the NU-37 bundle value [9]. The buckling strength of the RU-43 fuel bundle was assessed using the SIECC code. The calculation showed that the outer fuel rods of RU-43 will not buckle, and the excessive bending of fuel rods that can lead to bundle sticking is not expected to occur during normal operation [9].

TABLE 2. ROFEM PREDICTION OF RU-43 FUEL ROD PERFORMANCE IN CANDU-6 REACTOR

Parameter	**Design Basis or Requirement**	**ROFEM Prediction (Maximum Value)**
Fuel temperature	It shall be kept below the melting temperature of UO_2 (3123 K)	1642.0 K [1)] 1633.0 K [2)]
Sheath temperature	It shall be kept below the oxidation acceleration temperature (623 K)	595.0 K [1)] 599.0 K [2)]
Rod internal gas pressure	It shall not exceed system pressure (10.6 MPa)	1.11 MPa [1)] 1.00 MPa [2)]
Total hoop strain of sheath	Max. 1%	(0.28 % at mid-pellet, 0.80 % at ridge) [1)] (0.15 % at mid-pellet, 0.74 % at ridge) [2)]
Plastic hoop strain of sheath		(0.0 % at mid-pellet, 0.13 % at ridge) [1)] (0.0 % at mid-pellet, 0.07 % at ridge) [2)]
Sheath ridge height		0.0334 mm [1)] 0.0318 mm [2)]
Sheath strain after discharge at STP (mid-pellet)	-0.8-0.5% and 0.09% average for outer rod from 20 years experience [17]	(-0.49 % at mid-pellet, -0.07 % at ridge) [1)] (-0.60 % at mid-pellet, -0.18 % at ridge) [2)]
FGR after discharge at STP	0-8% and 2.6% average for outer rods from 20 years experience [17]	0.45% [1)] 0.35% [2)]

[1)] Value for inner rod.
[2)] Value for outer rod.

The ANSYS commercial computer code has been used to assess and compare the strength of a RU-43 fuel bundle with a NU-37 bundle during a refuelling operation [10]. ANSYS results, in general, show that the strength of the RU-43 fuel bundle is as good as that of the NU-37 fuel bundle. This reveals that RU-43 fuel bundles are able to withstand extremely high flow rates without showing a significant geometric instability.

The hydraulic pressure drop along the fuel channel is due to two components of concentrated and distributed friction losses. A complete analytical hydraulic pressure drop model has been developed (DELTAP code) [11]. It considers the contribution of the end plates, spacers and fuel rods to friction loss. Using this model, the RU-43 coefficient pressure drop has been calculated and the resulting value

was lower than the respective value for the NU-37 bundle. Excessive flow-induced vibrations of the fuel rods and of the bundle can cause fretting damage to pressure tubes and to bundle components. Excessive vibrations can also threaten the bundle integrity via fatigue of the assembly welds or of the endplate. For these reasons, the vibration amplitudes of the RU-43 bundle were assessed with the VIBFAS code [12]. The traverse (lateral) vibrations of the RU-43 fuel rods were compared to the NU-37 vibrations. The smaller diameters of the RU-43 fuel rods tend to increase the vibration amplitudes in RU-43 fuel. On the other hand, the RU-43 bundle contains comparatively more open sub-channels. This leads to lower coolant velocities in the RU-43 sub-channels which, in turn, tend to decrease the vibration amplitudes. The overall result is that the net traverse vibrations of RU-43 rods are expected to be similar to those of the NU-37 fuel.

5. Safety implications and power pulse analyses

The implementation of RU-43 fuel in a CANDU-6 reactor would have an overall beneficial effect in terms of safety margins during postulated reactor accidents. The main reason for this benefit is the reduction of more than 20% in the outer rod linear powers of the fuel bundle, compared with the outer rods of a NU-37 bundle. The effect of this reduction in rod linear powers is that fuel temperatures, sheath temperatures and fission product releases will all be lower for most design basis accidents.

The lower initial fuel temperatures will result in lower peak fuel center line temperatures, thereby increasing the margins to fuel center line melting. In addition, lower fuel temperatures will result in lower fuel string axial expansion, increasing channel integrity margins. Similarly, peak sheath temperatures of RU-43 are expected to be lower than the peak sheath temperatures of NU-37. The lower fuel and sheath temperatures will result in lower fission product releases to the fuel-to-sheath gap, which will lead to fewer fuel failures and lower doses during a postulated large break Loss-of-Coolant Accident (LOCA). Because of the lower sheath temperatures, pressure tube temperatures will also be lower, resulting in less pressure tube/calandria tube contacts, and thus providing greater safety margins for channel integrity.

Because of the lower outer rod linear power ratings of the RU-43 fuel, as compared with those of RU-37 fuel, there is a potential for an increase in CANDU-6 reactor power without a decrease in safety margins. Consequences of a postulated large LOCA were used as an indicator to determine the power increase potential of RU-43 fuel [13,14].

Analyses were performed for two large break LOCA scenarios with shut down systems and emergency core cooling (ECC) available; these scenarios were a 20% reactor inlet header (RIH) break and a 80% reactor outlet header (ROH) break. ROFEM code calculations [15] were performed to estimate steady-state fuel rod conditions at the onset of the accident. Then, after the onset of the accident, the fuel and fuel-sheath behaviour of the outer fuel rods residing in the core pass downstream of the break (i.e., critical core pass) were evaluated by the CAREB code [16].

Typical fuel behaviour following an 80% ROH break is shown in Figs 6 and 7 for a rod in the outer ring. The fuel rod burnup at the time of the accident is assumed to be 355 MW•h/kg U when the internal pressure has its maximum value.

Figure 6 shows the temperature transients for the center line and the sheath. The maximum fuel center line temperatures for the RU-43 and standard fuel (1287 ^{0}C and 1650 ^{0}C, respectively) are well below melting and occur both earlier in transient, at 4 seconds. The maximum sheath temperatures for the RU-43 and NU-37 fuel are 1182 ^{0}C and 1190 ^{0}C, respectively, and occur both at 14 seconds. The lower maximum fuel center line and sheath temperatures of the RU-43 bundle fuel are attributed to the lower stored heat caused by the lower maximum linear rod power for the (ring power flattened) RU-43 fuel bundle as compared with the standard fuel bundle. The rod internal pressure predicted by CAREB is provided also in Fig. 7. This Figure also shows the evolution of sheath hoop strain and stress. The standard fuel rod is predicted to fail at 31 seconds after the event.

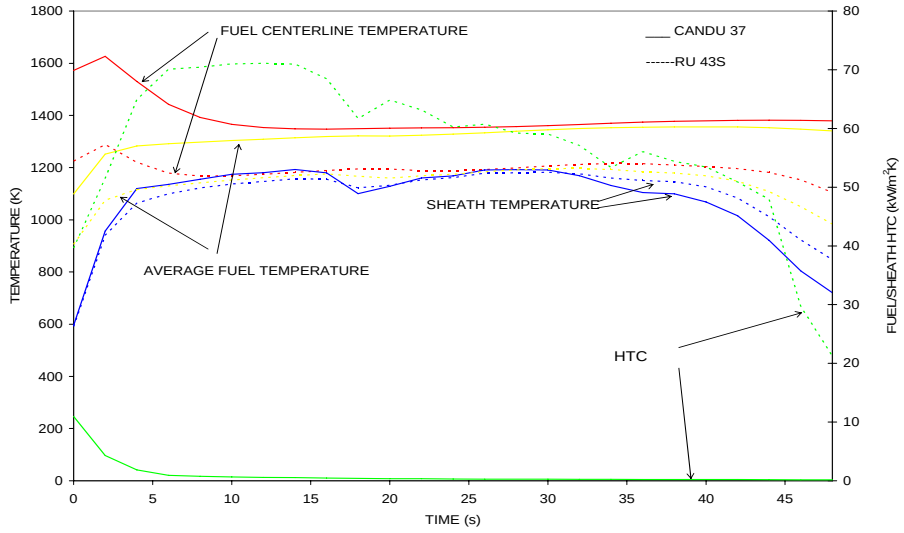

FIG. 6. Selected analyses parameters versus time during 80% ROH accident for outer rod of NU-37 fuel bundle ("CANDU 37") and for outer rod of RU-43 fuel bundle ("RU 43S") (CAREB results).

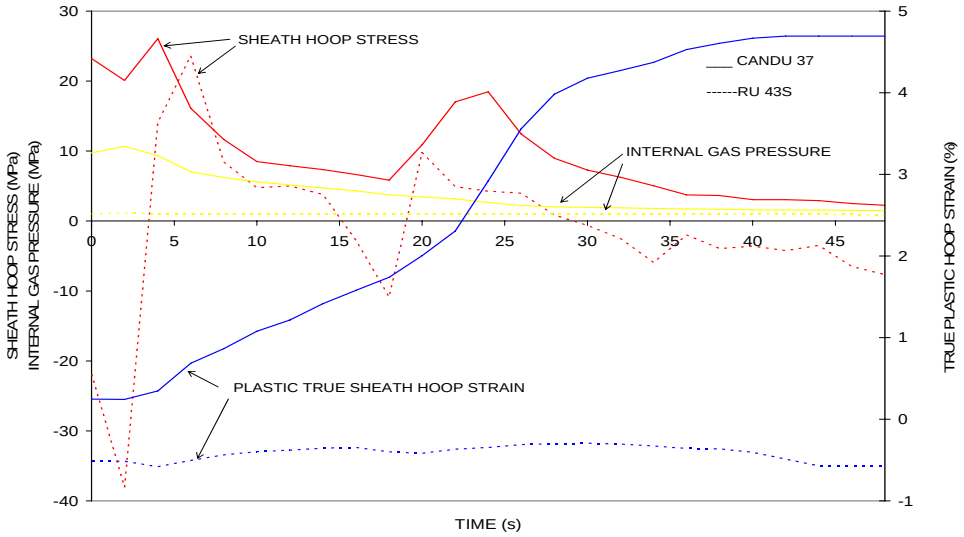

FIG. 7. Selected analyses parameters versus time during 80% ROH accident for outer rod of NU-37 fuel bundle ("CANDU 37") and for outer rod of RU-43 fuel bundle ("RU 43S") (CAREB results).

According to the analysis of a 20% RIH break and a 80% ROH break the power in a channel within a full core of RU-43 fuel bundles can be increased to 110% of the initial power at which the internal gas pressure in outer rods is approximately equal or little lower than the internal gas pressure of the NU-37 fuelled channel.

In conclusion, there is uprating potential available with a core made up of RU-43 fuel bundles, and the consequences of a large break LOCA for the uprated RU-43 core would be no worse than the consequences after a large break LOCA for an NU-37 fuelled core at nominal power.

The sheath strains predicted by CAREB are significantly below the 5% failure criterion. Therefore, sheath failure caused by excessive straining is precluded.

6. Experimental programme

Out-of- reactor tests

The hydraulic and mechanical integrity of the RU-43 fuel bundle design has been verified through various out-of-reactor tests conducted in the Hot Test Loop Facility of INR Pitesti to show that the RU-43 bundle design meets the design requirements of the CANDU-6 reactor fuel and that it is also compatible with the CANDU-6 fuelling machine. The present effort of the INR Pitesti is concentrated on the mechanical flow testing of prototype RU-43 bundles. The hydraulic performance of the bundle will be verified in the fuel string pressure drop test, and the mechanical integrity of the bundle will be demonstrated in the bundle strength test, refuelling impact test, cross-flow test and endurance fretting test. The final "acceptance" test for fuelling machine compatibility involves the use of an actual CANDU-6 fuelling machine.

The fuel string pressure drop test will be a single phase, high pressure, light water test for a fuel channel loaded with RU-43 bundles. The pressure measurements will be performed for both RU-43 bundles and reference NU-37 bundles to compare the test results under the same test environment. The acceptance criteria for the test is that the most probable fuel channel pressure drop should not exceed 718 kPa at the reference condition (mass flow of 24 kg/sec and density of 781 kg/m^3) for the CANDU-6 reactor.

The main objective of the fuel bundle strength test is to determine whether the bundle will withstand the normal and abnormal loads imposed during refuelling and whether the bundle can be discharged from the reactor without difficulty after being exposed to abnormal refuelling loads (the double side-stop test) and abnormal fuel loading (the single side-stop test). The amount of outer rod bowing and general bundle shape distortion of the fuel bundle will be determined for each test. The acceptance criteria are that the test bundles maintained their structural integrity and no significant distortions were observed. The test bundles must pass through the kinked tube test, which is used as an acceptance check for all bundles at final inspection.

During the normal refuelling sequence in a CANDU-6 reactor, a new bundle is accelerated over a short distance by the coolant flow as it passes through the whole upstream liner region of the fuel channel. The bundle then hits the stationary bundles that are already in the channel. The objectives of the impact test are to demonstrate that the fuel bundles can withstand this impact without significant damage. The severity of the impact increases with bundle velocity, which depends on the acceleration distance and coolant flow. After impact tests the dimensional changes of the fuel rods and the end plane profile must be all within the specified requirements and the visual examination of the pressure tube must show no marks as a result of the test.

A 3000 hour fretting-and-vibration endurance test will be performed under representative in-reactor temperature and pressure conditions (266 ^{0}C, 11.0 MPa inlet pressure and 30 kg/sec flow rate). This test is done to verify that the fretting wear of the pressure tube and RU-43 bundle is acceptably low under such conditions.

In- reactor experiments

In order to demonstrate the performance of the RU-43 fuel rods and to prove the adequacy of the manufacturing technologies, experimental fuel rods will be introduced into the irradiation devices of the TRIGA MT reactor of INR Pitesti. Declining power history tests and power ramp tests are designed in conditions equal to those anticipated for RU-43 fuel in the CANDU-6 power reactor. In addition, INR Pitesti is planning to perform highly instrumented fuel rod tests in order to provide information regarding the evolution of fuel centre temperature, fission gas pressure and fuel rod dimensions during irradiation.

7. Conclusions

1. The major features of the RU-43 fuel bundle design are to use RepU and increase the number of fuel rods to 43, compared with 37 rods in the NU-37 standard bundle. A recently developed advanced RU-43 fuel bundle has major design improvements over the NU-37 bundle.
2. Analysis has shown that for a CANDU-6 reacto, average discharge burnups almost double when RU-43 fuel is used. The burnup goes from 170 MW•h/kg U with natural uranium fuel to about 355 MW•h/kg U with RU-43 fuel. Therefore, the use of RU-43 fuel in CANDU-6 reactors potentially offers economic, environmental and public acceptance benefits. The use of RepU significantly increases the burnup, thereby increasing resource utilization and reducing fuel requirements. Spent fuel volumes and overall fuel cycle costs are both reduced.
3. The results of the 1000 FPD core follow show that RU-43 fuel containing 0.96 w/o ^{235}U used with a 4-bundle-shift refueling scheme would be satisfactory fuel in an equilibrium CANDU-6 core. It would not cause excessive channel or regional overpowers, or significant risk of fuel rod failure in spite of its high burnup and the slightly higher ^{235}U content than that of natural uranium fuel.
4. Fuel defect analysis suggests that, while this fuel would experience positive linear rod power boosts at burnups in the range of 100 to 355 MW•h/kg U, there is no significant risk of fuel rod failures. Indeed, the large margin of linear rod powers to the CALUB threshold suggests that this fuel will perform well.
5. Fuel performance analysis indicated that the RU-43 fuel with extended burnups would show as good in-reactor performance as standard NU-37 fuel rod does, because the fuel temperature and rod internal pressure are far below the design criteria. The sheath strain and fission gas release are lower than those found for fuel rods of NU-37 bundles. Fatigue failure of the rod subjected to a significant number of power cycles will not occur. The vibration amplitudes of RU-43 bundles are expected to be acceptably small and similar to those of the NU-37 fuel bundles. Fatigue failure at the endplate weld and the end plate web (grid) due to lateral vibration of fuel rods subjected to axial flow of coolant in CANDU-6 reactors will not occur in the RU-43 fuel design.
6. The finite element (FE) model analysis with the ANSYS computer code demonstrated that the RU-43 fuel bundle will maintain a stable geometry under normal operating conditions. The bundle has sufficient strength to withstand the expected in-reactor mechanical and hydraulic loads. The RU-43 fuel bundle geometry will remain compatible with all interfacing components.
7. The effect of each design change of the RU-43 bundle on the CANDU-6 reactor safety has been assessed for representative accident scenarios. The maximum sheath temperature and maximum sheath strain for the cases analyzed are less than specific safety limits. The amount of fission product release, and so the dose to the public, are reduced significantly compared to standard fuel due to the reduction of the initial gap inventory and the number of failed fuel rods. There is an uprating potential available with a RU-43 fuelled core, and the consequences of a large break LOCA for the uprated RU-43 core would be no worse than the consequences after a large break LOCA for a NU-37 fuelled core at nominal power.
8. The hydraulic and mechanical integrity of the RU-43 fuel bundle design has been verified through various out-of-reactor tests conducted in the Hot Test Loop Facility of INR Pitesti to show that the RU-43 bundle design meets the design requirements of the CANDU-6 reactor fuel and that it is also compatible with the CANDU-6 fuelling machine. In order to demonstrate the performance of the RU-43 fuel rods and to prove the adequacy of the manufacturing technologies, experimental fuel rods will be introduced in the irradiation devices of the TRIGA MT reactor of INR Pitesti.

In final conclusion, the use of RU-43 fuel bundles in a CANDU-6 reactor has beneficial environmental impacts on the overall nuclear fuel cycle. This is an excellent example of the environmental “3 Rs” (Reduce, Reuse, Recycle) as applied to the global nuclear energy use.

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ECONOMICS, MARKET ASPECTS AND LONG-TERM PERSPECTIVES OF RepU UTILIZATION

(Session 6)

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The current status of reprocessing plants and MOX fuel fabrication facility in Japan

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[b] Conversion facility decommissioning section in Ningyo-toge,
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Abstract. Japan has two reprocessing plants: The Tokai reprocessing plant (TRP) is in operation and the Rokkasho reprocessing plant (RRP) is in final test before start-up. TRP is owned by the Japan Atomic Energy Agency (JAEA). It is in operation since 1977. By March 2007, this plant had reprocessed spent fuel totalling 1136 t HM. JAEA has been thinking about four methods to utilize reprocessed uranium (RepU): its re-enrichment, its usage in form of mixed uranium-plutonium oxide (MOX) fuel, the mixing of this RepU with the depleted uranium and its storage. This paper introduces the MOX fuel fabrication technology obtained by the Tokai Works. On the other hand, Japan Nuclear Fuel Ltd. (JNFL) decided to construct a new reprocessing plant at Rokkasho-mura. The Rokkasho reprocessing plant is currently undergoing final commissioning tests and is planned to start operation in November 2007. Furthermore, JNFL will have constructed the MOX fuel plant by 2012. This paper will provide the current status of RRP and the near-future perspectives for the RepU in Japan.

1. Introduction

Japan started the research on nuclear power generation in the middle of the 1950s. A test power reactor named Japan power demonstration reactor (JPDR) started operation in 1963 and the Tokai power station, the country's first commercial reactor, went into commercial operation in 1966 with a generation capacity of 166 MW(e). Currently, 55 commercial nuclear reactors are in operation with a total generation capacity of 49 580 MW(e) and about one-third of Japan's electricity comes from nuclear power. Japan will continue to develop nuclear power as a mainstay of non-fossil energy, while placing the highest priority on safety.

Japan Atomic Energy Agency (JAEA) has successfully operated the Tokai reprocessing plant (TRP) (introduced from French technology) since the start of the hot test operation in 1977. By March 2007, this plant had reprocessed spent fuel totalling about 1136 t HM. The research on, and development of plutonium fuel in Japan started in January 1966 with 260 grams of plutonium brought into the Plutonium fuel development facility (PFDF) at JAEA's Tokai Works. Later, after Japan-US bilateral nuclear negotiations, JAEA started the original method to produce mixed uranium-plutonium oxide (MOX) fuel.

The construction of Japan Nuclear Fuel Ltd.'s (JNFL) Rokkasho reprocessing plant (RRP) is based on the operational experience accumulated at TRP and on the technologies and experiences from advanced countries. The plant is currently undergoing final activity tests and will start operation later in 2007. JNFL is also constructing a MOX production plant, with the applied technologies introduced by JAEA. This plant will start operation in 2012.

2. JAEA's experiences in reprocessing and MOX fuel fabrication

2.1. Reprocessing plant

TRP uses the plutonium and uranium recovery by extraction (PUREX) process which has become the most common reprocessing technology. PUREX involves the dissolution of irradiated nuclear fuel in nitric acid, followed by the separation of the uranium, plutonium, and fission products by solvent extraction using a mixture of tributyl phosphate in organic diluents.

FIG. 1. Tokai reprocessing plant.

2.1.1. Operating license

- Capacity: Maximum 120 t Upr/year; maximum 0.7 t Upr/day ('t Upr' means counted mass in tonnes metallic uranium before irradiation).
- Initial enrichment (of fresh fuel): 4 w/o ^{235}U.
- Cooling time of spent fuel: More than 180 days.
- Burnup: Maximum 35 000 MW•d/t Upr; less than 28 000 MW•d/t Upr/day.

2.1.2. Process flow

PUREX facilities have process functions which are similar to each other, including irradiated fuel element chopping, fuel dissolution, solvent extraction and process liquor storage.

The feature of TRP is to produce MOX rather than pure plutonium. Therefore, the denitration method by direct microwave heating (MH) method is adopted [1]. This method has provided excellent results.

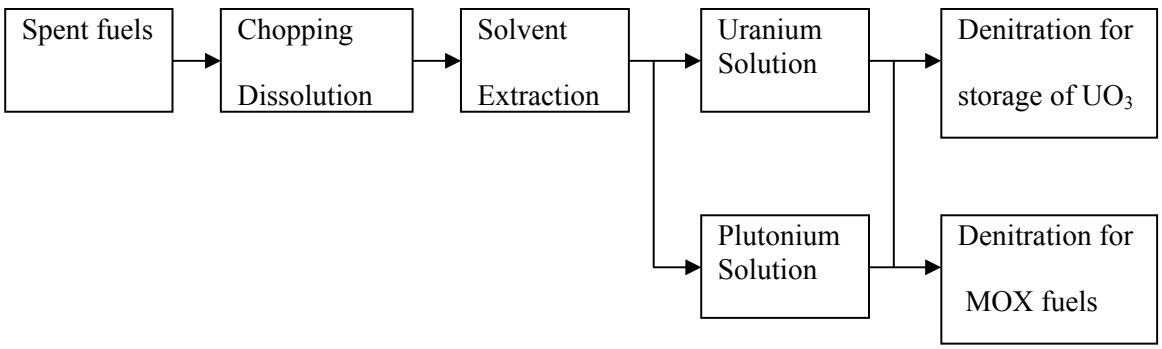

FIG. 1. Flowchart of reprocessing process applied at Tokai reprocessing plant.

2.1.3. Achievements

TRP has been developed to separate uranium and plutonium from spent fuel and to recover them for the purpose of making efficient use of available uranium resources. RepU can be reused together with plutonium as new fuel. Therefore, reprocessing plays a key role in the nuclear fuel cycle.

Until the end of March 2007, TRP had reprocessed about 88 tonnes of ATR (Fugen) spent fuel, about 644 tonnes of BWR fuels, about 376 tonnes of PWR fuels, and about 9 tonnes of fuel from JPDR [2].

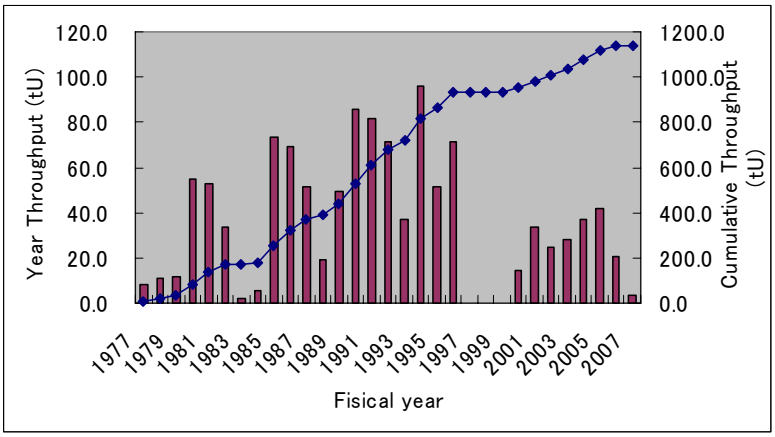

FIG. 2. The overall achievements at the Tokai reprocessing plant.

2.2. Conversion of uranium and plutonium mixture

The MH method was originally developed by JAEA. The possible chemical reaction is shown below, and the process flows are indicated in Fig. 3.

$$UO_2(NO_3)_2 \cdot 6H_2O \rightarrow UO_2(NO_3)_2 \cdot 3H_2O + 3H_2O$$

$$UO_2(NO_3)_2 \cdot 3H_2O \rightarrow UO_2(OH)NO_3 + HNO_3 + H_2O$$

$$UO_2(OH)NO_3 \rightarrow \beta\text{-}UO_3 + 0.5H_2O + NO_2 + 0.25O_2$$

And/or

$$UO_2(OH)NO_3 \rightarrow \beta\text{-}UO_3 + HNO_3$$

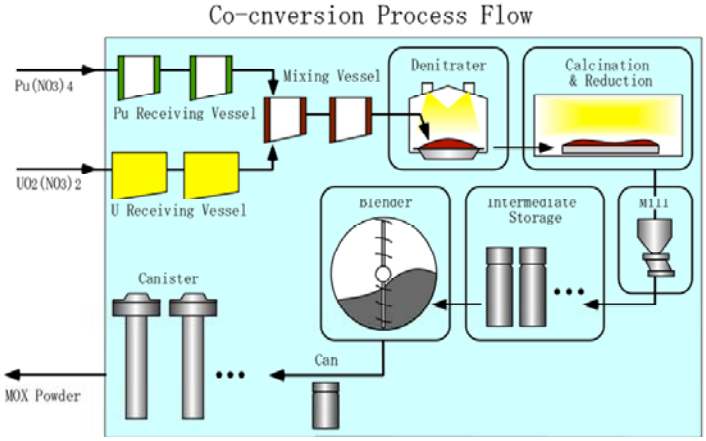

FIG. 3. The process flow of denitration by the microwave heating (MH) method.

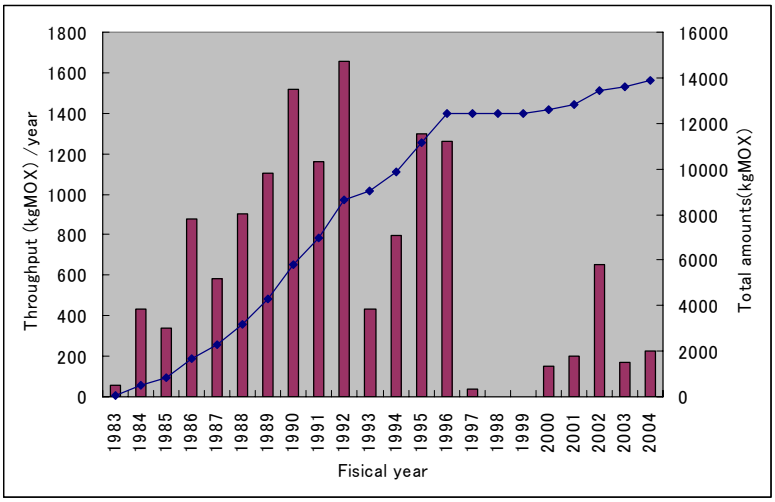

FIG. 4. Total annual and cumulative MOX fuel produced via co-denitration of uranium and plutonium by the microwave heating (MH) process.

Until August 2006, JAEA had produced MOX fuel totalling about 13.9 t HM (see Fig. 4).

2.3. MOX fuel

JAEA has developed plutonium fuel fabrication technologies through MOX fuel production for the experimental fast reactor 'Joyo', the prototype Fast Breeder Reactor (FBR) 'Monju' and the advanced thermal reactor 'Fugen' at different plutonium fuel fabrication facilities. The accumulated number of the MOX fuel assemblies fabricated in these facilities has amounted to approximately 1700.

JAEA's MOX fuel fabrication infrastructure comprises three facilities, namely the Plutonium fuel development facility (PFDF) (see Section 1.), the Plutonium fuel fabrication facility (PFFF) and the Plutonium fuel production facility (PFPF). JAEA has 30 years of experience in MOX fuel fabrication. The total amount of MOX fuel fabrication reached approximately 170 tonnes as of the end of December 2001 (see Fig. 5). No fuel pin failure has been found after irradiating this MOX fuel.

JAEA has started the overall technical cooperation for Japanese MOX business to be undertaken by JNFL and will also provide technical support for its stable operation.

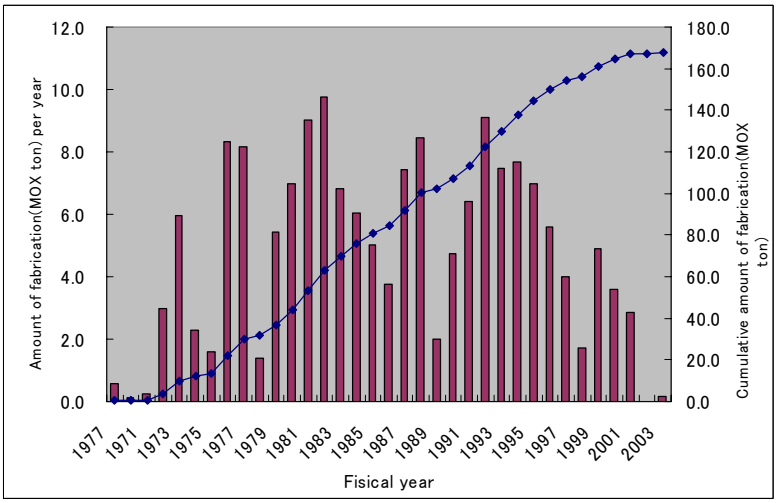

FIG. 5. Total annual and cumulative production of MOX fuel by JAEA.

2.4. Status of near-term MOX program

The Japanese Federation of Electric Power Companies (FEPCO) has a plan to use MOX fuel in 16 to 18 nuclear power plants (NPP) by 2010 – primarily for the usage of plutonium recovered in European reprocessing plants. In order to facilitate this MOX program, the country's Ministry of Economy, Trade and Industry (METI) decided to increase its subsidies to local governments that accept MOX programs for NPPs located in their area. However, this plan has been delayed due to the following two incidents: Tokyo Electric Power Company's (TEPCO) data falsification in 2003 and Kansai Electric Power Company's (KEPCO) steam pipe rupture accident at the Mihama NPP in August 2004. As a result, the MOX programs of two major utilities are stopped at present.

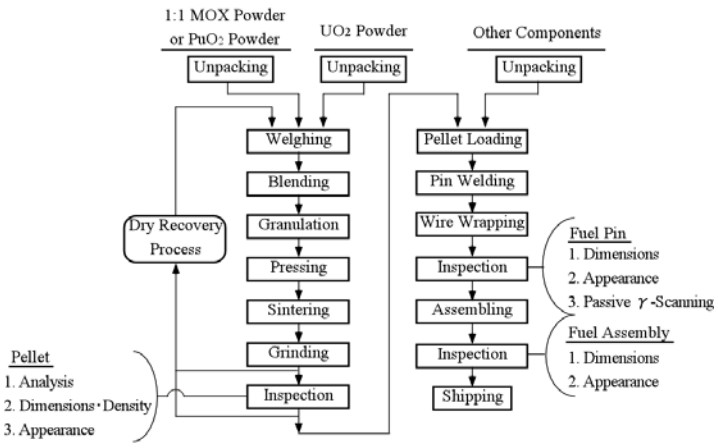

FIG. 6. Process flow of MOX fuel production by JAEA.

Some smaller utilities (Kyusyu, Shikoku and Chugoku Electric Power Company) are in the early stages of their own MOX programs. Kyusyu Electric Power Company, for example, announced that it will load MOX fuel into the Genkai NPP as early as 2010. At present, there is no specific plan to reprocess spent MOX fuel, although the long-term policy is to recycle plutonium from spent MOX fuel as well. Most likely spent MOX fuel will be stored during the foreseeable future.

JAEA, the owner and operator of the 'Monju' fast breeder prototype reactor (280 MW(e)), is now preparing the plant's restart after almost 10 years of negotiations with the local government. The legal efforts by opposition groups to prevent this restart were lost in 2005 when the Supreme Court made a final decision to endorse the safety licensing of Monju. JAEA plans to restart Monju around 2010, but the reactor's future operational schedule has not yet been finalized.

3. Reprocessing plant and MOX fuel at JNFL

3.1. Rokkasho reprocessing plant

RRP is currently undergoing final commissioning tests (see Fig. 7). JNFL will confirm the safety quality and the stability quality of the plant's equipment by using spent fuels at this final stage. The maximum reprocessing capacity of the plant is 800 t HM/year, which is enough to reprocess the spent fuel produced annually by 40 reactors of the 1000 MW(e) size. These 800t HM represent about 80% of the annual spent fuel arisings Japan.

3.1.1. Operating licenses

- Capacity: Maximum 800 t Upr/year; maximum 4.8 t Upr/day;
- Initial enrichment of fresh fuel: 5w/o ^{235}U;
- Average enrichment of spent fuel assembly: Less than 3.5 w/o ^{235}U;
- Cooling times of spent fuel: More than 1 years prior to delivery from NPP to RRP and more than 4 years before chopping;
- Burnup: Maximum 55 000 MW•d/t Upr; less than 45 000 MW•d/t Upr/day.

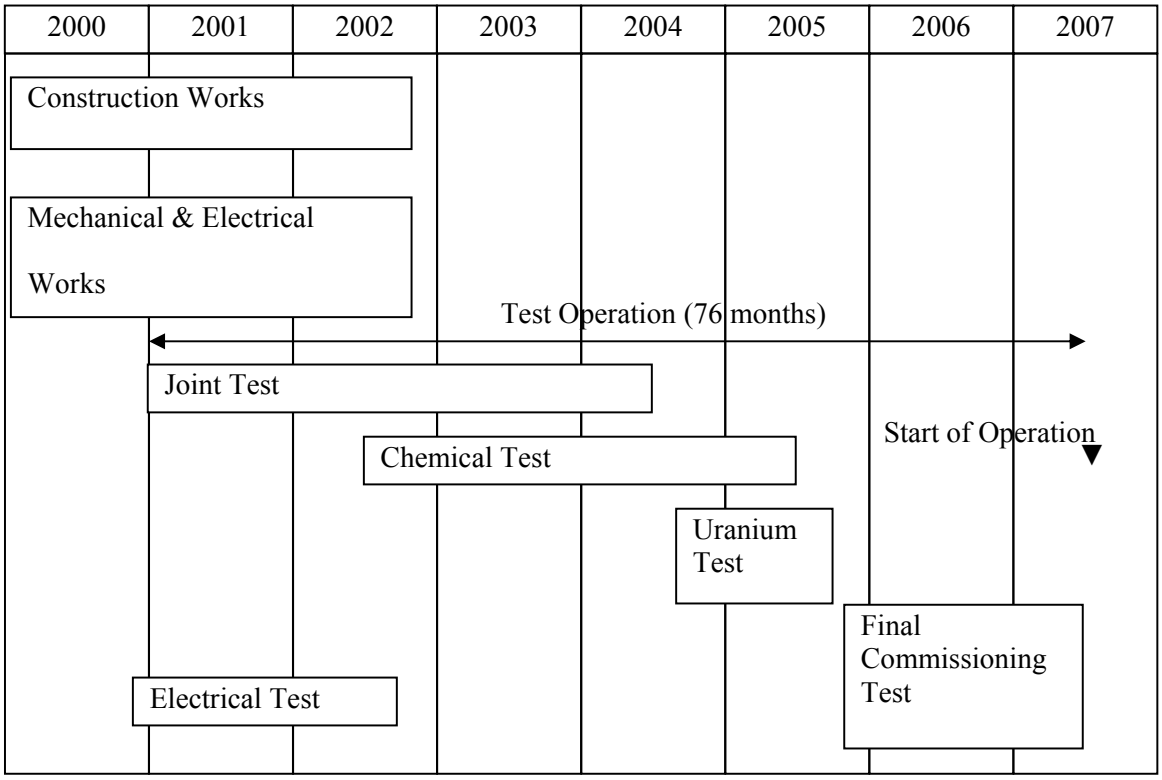

FIG .7. Construction schedule of the Rokkasho reprocessing plant.

Confirm the safety features of facilities and performance of equipment and installations

First step	Confirm using PWR fuel at line A of the shearing and dissolving facilities	Burn-up: low to medium. Cooling period: long to medium	Amount of spent fuel to be used about 30 tonnes
Second step	After confirmation using PWR fuel at line A, as well as BWR fuel.	Burn-up: low to medium. Cooling period: long to short	Amount of spent fuel to be used about 60 tonnes
Third step	Confirm at line B; mainly those items confirmed in the first and second step both fuel	Burn-up: low to medium. Cooling period: long to short	Amount of spent fuel to be used about 70 tonnes

Confirm the safety features and operational performance of the entire plant

Fourth step	Confirm the reprocessing capacity, etc. of the entire plant using PWR fuel	Burn-up: low to medium. Cooling period: medium to short	Amount of spent fuel to be used about 110 tonnes
Fifth step	Confirm the processing capacity, etc. of the entire plant using BWR fuel	Burn-up: low to medium. Cooling period: long to short	Amount of spent fuel to be used about 160 tonnes

FIG. 8. Final commissioning test conditions.

3.1.2. Current situation

In 27 October 2006, JNFL performed a uranium-plutonium co-denitration test which is the most important phase of the final commissioning test shown in Figures 7 and 8. JNFL announced to start the generation of mixed uranium-plutonium oxide on 2 November 2007.

3.2. MOX plant

It has been verified that there are no significant differences between the characteristics of MOX fuel and uranium oxide fuel and that - on the basis of the experience and various data obtained - the safety of the reactors can be ensured with MOX fuel as well as with uranium oxide fuel. Given the current status of existing light water reactors (LWR), part of the uranium fuel in their cores can be replaced by MOX fuel. According to the current plan, Japanese electric power companies will implement the thermal recycling of plutonium by introducing MOX fuel into 16 to 18 of the Japanese operating NPP units.

Responding to a request of FEPCO, since December 1998 JNFL has been conducting domestic and international technological studies regarding the MOX fuel fabrication technology, thereby simultaneously investigating safety issues.

For example, when uranium with an enrichment of 3% ^{235}U is used as nuclear fuel, the spent fuel will contain 1% residual (unburned) ^{235}U and 1% newly produced plutonium. The spent fuel is chemically reprocessed at the reprocessing plant with the purpose of reusing the regained uranium and plutonium as nuclear fuel. RepU and plutonium are mixed with natural uranium or residual uranium (depleted uranium) arising at the enrichment facilities and fabricated into MOX fuel.

Such reprocessing can double the uranium utilization efficiency in LWRs. Moreover, the use of plutonium in fast breeder reactors offers excellent plutonium conversion efficiency and it is expected to significantly (by a factor of about 60) improve the future utilization efficiency.

3.3. JNFL's MOX fuel program

The unique feature in RRP is the uranium-plutonium co-denitration process. Due to this process, the plant does not produce plutonium as a single element, a fact which has considerable advantages for the nuclear non-proliferation. The operations of all reprocessing systems, located separately, are controlled and monitored at the central control room. The mainframe computer and the central control board enable efficient operation.

In April 2005, JNFL concluded ‘The Basic Cooperation Agreement for the Location of MOX Fuel Fabrication Plant’ with the Aomori prefecture and Rokkasho village, and a license application for MOX fuel fabrication business was submitted to the governmental authorities. The safety assessment is now in progress. The outline of the planned MOX fuel fabrication plant is as follows:

- Fuel product: MOX fuel for light water reactors (BWRs and PWRs);
- Maximum fabrication capacity: 130 t HM/year;
- Size of main building: approx. 80m x 80m; 3 underground levels, 1 ground level floor (partly two-storied);
- Number of operating employees: nearly 300;
- Expected start of operation: April 2012;
- Construction cost: approx. ¥120 billion.

4. The challenges and directions for nuclear energy policy in Japan

In December 2006, the Nuclear Energy Policy Planning Division in the Ministry of Economy, Trade and Industry (METI) published a report entitled 'The Challenges and Directions for Nuclear Energy Policy in Japan – Japan's National Nuclear Energy Plan' [3]. Main features of this report are listed in Sections 4.1. and 4.2.

4.1. Steady advancement of the nuclear fuel cycle and strategic reinforcement of nuclear fuel cycle industries

Work towards the early establishment of the LWR nuclear fuel cycle, including the necessary research and development, and efforts to gain the widespread understanding and cooperation of local residents and citizens nationwide will continue to be essential. Hereby the following five objectives are presented:

- Start of operations at the Rokkasho reprocessing plant, scheduled for August 2007;
- Introduction of the plutonium utilization in LWRs (using MOX fuel in LWRs) at 16–18 reactors by FY 2010;
- Introduction of a new-model centrifuge at the Rokkasho uranium enrichment plant by around 2010;
- Start of operations at a MOX fuel fabrication plant for LWRs in 2012;
- Selection of candidate sites for the construction of a facility for the final disposal of high-level radioactive waste.

Furthermore, Japan continues to establish the structure for an independent Japanese nuclear industry amid the trend towards an oligopoly in the international nuclear power industry and developments in the nuclear non-proliferation regime. It is described that the strategic reinforcement of RepU is the stage of preparation of the environment for conversion at overseas facilities, enrichment, securing consignees for reconversion works, etc.

4.2. Achieving and developing depth in technologies, industries and personnel

The measures concerning the development of a Japanese next-generation LWR with international competitiveness are introduced as follows:

- Have the public and private sectors jointly launch a feasibility study on developing a Japanese next generation light water reactor with an eye to the global market to prepare for the replacement demand from around 2030.
- The feasibility study should take about 2 years. After its completion, proceed to the full-scale development stage (about 7 years). This development of a next-generation LWR would constitute the first national project in Japan in about 20 years.

According to METI's report, the following should apply to the technologies to be developed:

- The project should be clearly focused, rather than trying to please everyone, and it should be consistent with the reactor type strategies of the electric power companies;
- The reactors should have world-class performance and economic efficiency, and incorporate breakthroughs with global appeal;
- The approach should incorporate the manufacturers, be based on user needs, and aim at a standardized reactor.

The project should contribute to the development of technologies and human resources as required for the NPP replacement demand from around 2030 onwards.

5. Conclusion

In Japan, the Tokai reprocessing plant is making progress steadily, thereby entering the new stage of studying higher burnup fuel. The Rokkasho reprocessing plant is going to start operation in 2007.

The microwave heating (MH) method which is JAEA's original method on the mixed conversion of uranium and plutonium produced excellent results and JNFL will construct the MOX plant in cooperation with JAEA.

METI launched new national energy strategies and consistently indicates the necessity of the development of the nuclear energy.

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Reprocessed Uranium: Commercial Resource or Liability

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Abstract. The presence of minor uranium isotopes and their daughter products in reprocessed uranium (RepU) has logistics and cost implications for the recycle of the material. Whether or not RepU has a net asset value depends on the extent of any fuel service premiums that may apply, as well as on the evolution of prices in the various sectors of the fresh uranium fuel cycle route. Natural uranium prices today make RepU recycle look attractive but prices can and will change in the future. In addition, the economic view of recycle varies depending on whether or not the material is already recovered and stockpiled, or if it is a prospective product that could be recovered in existing or possible new reprocessing plants. This paper provides, in overview, a basis for assessing the conditions under which RepU may be considered a resource or a liability, as well as perspectives on the future evolution of front end commodity and service prices and the implications for the economic interest in recycle.

1. Introduction

After years of apparent denial on the buyer side of the market, events of the last few years have finally brought into focus the sharp reality that current operating and firmly identified uranium supply projects are insufficient to meet worldwide reactor requirements. Spot prices for uranium concentrates have increased 12-fold over the last four years.

The relative competitiveness of alternative supply sources accordingly has changed. For many years, in reactors across Europe and in Japan, there have been modest programs for recycling the products recovered in spent fuel reprocessing – reprocessed uranium (RepU) and plutonium. In today's tight market, alternatives to fresh uranium supply have become more attractive.

Substantial quantities of RepU exist but there is limited industrial infrastructure to support recycle and not all reactors are licensed to use such products. Even where on technical grounds there are no problems, utility reluctance or unfamiliarity, national policy or perceived public opposition can inhibit the potential for recycle more broadly. Having said this, NAC firmly expects that current inventories and future quantities of RepU to be recovered in reprocessing are set to enter the market on a larger scale.

2. Availability of RepU

Through 2006, approximately 30 000 t HM of spent fuel had been reprocessed in the reprocessing plants of British Nuclear Fuels plc. (BNFL), AREVA NC and Japan Nuclear Fuel Cycle Development Institute (JNC) at the Sellafield, La Hague and Tokai Mura sites, respectively. Of this something like 6000 t HM has been recycled already and approximately an additional 2000 t HM has been swapped in the Russian Federation and the USA by European utilities.

Today the inventory of RepU outside the Russian Federation and the USA, therefore, amounts to perhaps 22 000 t HM and more is going to be recovered in reprocessing in the coming years. Most of the current inventory has a residual ^{235}U content ranging from about that of natural uranium up to about 1% ^{235}U.

In the future additional RepU will be recovered, in Europe and in Japan. On the assumption that:

- Electricite de France (EDF) continues to reprocess at about the current annual level of 850 t HM through 2020;
- the Rokkashomura Reprocessing Plant (RRP) builds up to an equilibrium annual throughput of about 800 t HM by 2012; and
- the Nuclear Decommissioning Authority's thermal oxide reprocessing plant (THORP) completes current commitments.

Through 2020 something like an additional 22 000 t HM of RepU will be recovered in Western reprocessing plants, of which more than half will be French-owned and up to 40% Japanese-owned. On this basis the total amount of RepU available through 2020, excluding RepU recovered in the Russian Federation, will be approximately 45 000 t HM. However, the average quality of the RepU recovered in the future is expected to diminish[1] as average spent fuel burnups progressively increase.

3. Technical issues in RepU recycle

RepU contains minor isotopes of uranium (^{232}U and ^{236}U) that are not present in natural uranium. In addition, ^{234}U is present in concentrations that are much higher than in natural uranium. ^{232}U has a long radioactive decay chain that, at one point, includes Thallium-208 (^{208}Tl). ^{208}Tl emits a gamma ray with an energy of 2.6 MeV, which poses a significant potential external radiation hazard. ^{234}U represents an airborne alpha radiation hazard and accordingly poses an internal dose problem (e.g. in a powder conversion plant).

The main logistics issue is one of scheduling, so as to minimize the dose uptake problems associated with the build-up of daughter products from ^{232}U. In conversion to UF_6, thallium is left behind because it does not form a volatile fluoride, as does uranium (uranium hexaflouride (UF_6)). All of the service providers from re-conversion through fabrication and delivery, therefore, have to be lined up to fast-track the processed uranium thereafter. In addition to the problems affecting the basic fuel service processes, there are potential problems with the so-called heel left in an empty transport cylinders if it is not dealt with soon after emptying.

In the transport sector there are no show-stopping issues but the precise requirements vary according to whether or not the RepU involved has a ^{235}U assay below or above 1% (criticality safety requirements) and also depend on how long the RepU has been stored (radiation shielding requirements).

4. RepU recycle infrastructure

To date there have been in total four different routes used for the recycle of reprocessed uranium, as summarized in Table 1. Three have involved actual re-enrichment in centrifuge facilities and one has involved blending with enriched uranium above the commercial low-enriched (maximum 5% ^{235}U) category.

In Pierrelatte (France), AREVA NC had facilities that were able to convert uranyl nitrate to UF_6 but these have been closed, leaving a gap in the industrial recycle infrastructure. It is understood, however, that AREVA NC is looking at the possibility of building a new re-conversion facility in France. Japan also may consider such a facility to complement the Rokkashomura reprocessing plant. Whether or not other players enter the RepU re-conversion arena remains to be seen.

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[1] Lower average residual ^{235}U content and higher ratio of ^{236}U/^{235}U.

TABLE 1. SUMMARY OF ROUTES USED FOR REPU RECYCLE

Route	End Use	Re-Conversion	Re-Enrichment	Fabrication
A	Europe	To UF_6 by AREVA NC	Urenco	AREVA NP Romans
B	Europe	To U_3O_8 by AREVA NC; to UF_6 by Rosatom in Tomsk	Actual Re-enrichment by Rosatom in Tomsk	AREVA NP Romans
C	Europe	To U_3O_8 by AREVA NC	By blending with non-weapons HEU in the Russian Federation	Fabrication by TVEL in Elektrostal (in one case just pelletizing and then rods plus assembly at AREVA NP Lingen)
D	Japan	To UF_6 by AREVA NC	Urenco	By MHI in Japan

5. Economics of RepU recycle

5.1. Recycle premiums

Some surcharges have applied to re-conversion, re-enrichment and RepU assembly fabrication in the past, on an individual basis, with the cost of re-conversion to UF_6 for re-enrichment being the most significant extra cost. For the integrated routes using facilities in the Russian Federation, effective surcharges are not necessarily visible. Market conditions for an overall fuel assembly have tended to be the relevant benchmark.

In order to assess the longer-term economic viability of RepU recycle, the actual re-conversion (to UF_6), re-enrichment and re-fabrication route in Western facilities probably is the relevant model to assume. Today the blending of RepU with higher enriched uranium in the Russian Federation is an established alternative but it may not be available over the longer term. In addition, it does not provide a meaningful economic benchmark today, due to the very different accounting rules applicable in the Russian Federation for determining the recognized cost of a service.

Taking the actual re-enrichment route as an example, therefore, an estimate of the economic breakeven point between fresh uranium fuel and RepU fuel may be calculated. It is dependent on the isotopic composition of the RepU (principally the ^{235}U content) and to a large extent on the cost for re-conversion. Enrichment and fabrication premiums play a secondary role. So far generally it has been assumed that the RepU itself is gratis, i.e., a consequence of reprocessing that was performed for other reasons. Indeed, RepU that is not recycled would have a negative value, since costs for a disposal route would be incurred.

Strictly speaking the economic value of recycling RepU should be assessed as one element of the overall cost associated with spent fuel management involving reprocessing and this certainly would be the case for any new entrant to reprocessing. For most of the last 20 or more years it has been a very minor component in the overall economic balance however, due to the low market prices for natural uranium.

Taking into account plausible ranges for natural uranium, fresh uranium fuel cycle service costs, applicable costs for re-conversion to UF_6 and the premiums for other recycle services, Figure 1 shows an approximate comparison between the costs of enriched reprocessed uranium (ERU) and enriched natural uranium (ENU) for a nominal product at 4.25% ^{235}U. An allowance is included for a fuel fabrication premium in the case of the RepU.

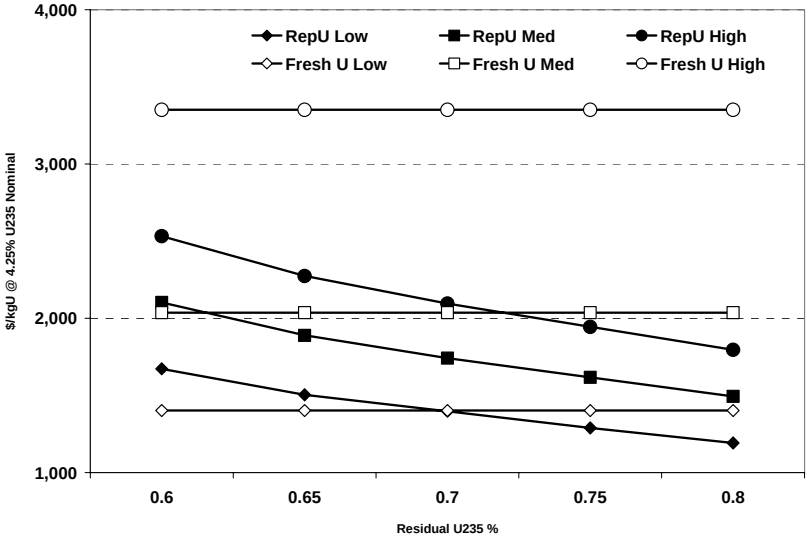

FIG. 1. Comparison of ERU and ENU fuel costs for nominal product at 4.25% ^{235}U.

The range shown for the residual ^{235}U content of the RepU feed does not go below 0.6%. This is because the over-enrichment needed for RepU below this quality in general would result in an actual product enrichment exceeding 5% ^{235}U to achieve equivalence with a nominal 4.25% ^{235}U product made from natural uranium. This does not mean that lower RepU quality could not be used in some applications with lower nominal enrichments but for simplicity in this example, results for the lower assays have not been calculated. Using these data, the RepU residual ^{235}U assays at which economic benefit would accrue would be approximately as shown in Table 2.

TABLE 2. ESTIMATED REPU MINIMUM RESIDUAL ^{235}U ASSAYS FOR ECONOMIC BENEFIT IN RECYCLE

Fresh Fuel Service Prices [a)]	**Recycle Price Premiums**		
	Low	**Medium**	**High**
Low (30/10/100)	> 0.7% ^{235}U	Not Economic	Not Economic
Medium (50/12.5/125)	> 0.6% ^{235}U	> 0.6% ^{235}U	> 0.7% ^{235}U
High (100/15/150)	> 0.6% ^{235}U	> 0.6% ^{235}U	> 0.6% ^{235}U

[a] $ per lb U_3O_8 / UF_6 Conversion - $ per kgU / $ per SWU.

Based on these estimates, the indication is that some reduction in average RepU quality can be tolerated without eliminating the economic incentive to recycle the material. Thus, planned average burnup increases should not discourage planning for major recycle over the longer term.

5.2. Projected conditions for the natural uranium market

NAC forecasts that the price of U_3O_8 will reduce considerably compared to today's prices. The exact profile for future prices no one can predict. For the purpose of this economic analysis some broad price assumptions, based on NAC detailed market forecasts, have been made as follows:

- 2007-2010: U_3O_8 high, UF_6 medium, SWU high; and
- 2011 onwards: U_3O_8 low to medium, UF_6 medium, SWU medium to high.

If these conditions were to apply and if the necessary recycle infrastructure were available, the margin between fresh fuel costs and RepU costs over the period through 2010 could be large ($1200 to $1700 per kgU depending on the RepU quality and RepU premiums). As and when natural U_3O_8 prices subside, this margin is forecast to reduce to no more than about $400 per kgU and it could disappear completely, or even go slightly negative.

At a level of $400 per kgU, if the future annual output from La Hague and Rokkashomura plus about 1000 t HM per year of RepU from inventory were recycled each year, using the actual re-conversion and re-enrichment route, the overall economic benefit potentially accessible to utility customers could be in the order of $100 million per year.

6. Future developments

New Western infrastructure investment will be needed if the supply potential of RepU recycle is to be realized, unless it is to be just a trickle-feed into the market over a very long period of time. The key investment area is re-conversion, to facilitate greater utilization of the Western centrifuge enrichment capacity capable of re-enriching RepU. In principle the Siberian Chemical Combine (SCC) facilities in Seversk (Russian Federation) – which may be constrained today – could be augmented to handle a greater annual throughput but this may not be acceptable, or possible, for political/institutional or indeed commercial/competitive reasons. What actually happens crucially will affect the extent of competition and price levels available for recycle services.

Having acknowledged the advantages of competition, it has to be said that any supplier considering new investment in re-conversion capacity must be prudent. Once uranium markets settle after the current price highs, the economic incentives to recycle potentially could be marginal.

7. Conclusions

There is considerable activity in the RepU recycle arena. The established industrial players that have some involvement with this field are looking at a range of initiatives to increase the Western supply capability, albeit in some cases in tandem with the Russian industry. With RepU becoming a more significant issue/opportunity, suppliers may be able to gain competitive advantage with some customers across all front end sectors if they can offer an attractive solution for handling RepU. It remains to be seen if any other industrial concerns will enter the arena for this reason.

What is clear is that in the current very tight uranium concentrates market, the addition of larger volumes of RepU to the supply side would have been beneficial in controlling uranium price increases but the recycle infrastructure has been limited. Those utilities that invested in reprocessing in earlier years today have the potential to benefit in the future by recycling their RepU, depending on the prices for recycle services offered by the suppliers. The extent of competition will determine how the overall economic benefit is shared between suppliers and the owners of the RepU.

Can reprocessed uranium become the most natural substitute to uranium?

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Abstract. This paper performs a value-in-use assessment of reprocessed uranium (RepU) by applying the 'Customer Value Management' methodology. This represents a progressive and practical approach which formalizes in a stepwise manner the customer's requirements and preferences, and what values are relevant to him in the supplier's offering.

1. Introduction

The current rally in uranium price has generated questions about the availability of raw materials to fuel nuclear energy. Providing answers is not simple as the link between primary uranium demand and electricity generation by nuclear reactors is not a direct one. As compared to thermal power, a unique characteristic of nuclear energy is that recyclable fissile and fertile materials may be a substitute to uranium, its primary fuel source. Taking into account reenrichment of tails, recycling of fissile materials recovered during reprocessing and in core fuel management (stretching out), the elasticity between reactors electricity production and primary uranium demand could become quite significant.

According to OECD/NEA [1], "…If all the challenges and barriers to the recycling of available materials would be overcome, these materials could provide fuel for a fleet of current generation Light Water Reactors (LWR) with a total capacity of at least 100 GW(e) – roughly the US installed nuclear capacity – during nearly 40 years." The full extend of this secondary supply capability is far from being implemented. For the market, the primary uranium availability remains the only driver to address reactor demand. The recent natural uranium price evolution has sent a strong signal to the mining and nuclear industry, towards developing new uranium mines. As a result, more than 400 so-called 'uranium junior mining companies' popped up in the last few years. There is no market price for reprocessed uranium (RepU) and such a trend has obviously not been seen in the case of RepU.

Therefore the question: While the current primary supply market conditions would favour more general use of alternative supplies, why is the nuclear community not taking full benefit of this potential and notably by recycling the fissile uranium left unused in spent fuel?

As a matter of fact, while plutonium recovered during reprocessing operations is recycled without delay in MOX fuels, the nuclear community does not appear to be willing to rely on RepU to close the gap between reactor requirements and primary uranium production.[1]

To paraphrase the well-known statement evaluating how good nuclear is for curbing CO_2 emissions, one may say that if RepU alone cannot solve the current imbalance between demand and supply of natural uranium, it is certainly part of the solution. For this to occur, a strong effort of the entire nuclear community is certainly needed to pave the way for a larger use of the RepU resources and develop the needed industrial capacities accordingly.

[1] To the extent it is not a regulatory requirement.

How can this take place? This paper will try to provide some insights to answer this question from a marketing point of view, using a 'customer value management' (CVM)[2] methodology [2, 3], to evaluate the 'value drivers' of the RepU 'offering'. Therefore, the following is structured according to the CVM successive steps.

2. Need of a value-in-use assessment of RepU

To market a product, one has to bring it to the market in such a way as to 'deliver value to customers'. In the case of RepU, bringing the product to the market had not been an easy task. With natural uranium available at low cost up to the early 2000s, the investment needed to develop industrial capacities to bring RepU to the market would have made it a liability to utilities more than a quantified 'plus' in their fuel supply.

Therefore, conference papers or commercial communications between potential suppliers and customers of RepU mostly focussed on the hurdles in the use of RepU and all issues to tackle, rather than assessing the value-in-use of RepU.

With the uranium market now flying in the USD 100/lbU_3O_8 range and even above this level, there is a need for the market to reassess the value-in-use of RepU.

3. RepU offering and its benchmarking using the CVM methodology

3.1. Description of the RepU 'naked offering'[3] and available options

First of all one has to know what constitutes a recycling offering which in our case deals with RepU. Is it a product offering or a service offering? Does it start with the utility's used fuel and, therefore, includes back end services? Does it go up to fuel delivery? Can we see it as a series of services marketed independently of each other just as is the case in the front end markets?

At the end of the day what the utility needs is a fuel assembly with fissile material ready for loading in its reactor. From a utility fuel manager's point of view, the 'naked offering' should end with a packaged offer.

As regards RepU inventories, a substantial part belongs to the utilities, as part of treatment contracts signed with the operators of the reprocessing facilities at La Hague and/or Sellafield. Therefore, to end with a 'naked offering' - a fuel assembly ready to be loaded in the reactor - owners of RepU need to be provided with front end processing services (such as conversion plus enrichment or blending services) and fuel manufacturing. As of now the services provided are frequently limited to what is required for an interim storage of unspecified duration, an unsatisfactory 'wait and see' approach indeed.

In conclusion, the standard or naked offering considered for RepU is a packaged front end offering in the form of Enriched Reprocessed Uranium (ERU) fuel. Additional features can encompass logistics services, or embed a RepU proposal in a global fuel cycle services package, with front end and back end.

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[2] The 'customer value management' methodology is a progressive and practical approach which formalizes in a stepwise manner the customer's requirements and preferences, and what values are relevant to him in the supplier's offering.

[3] In the CVM methodology, 'naked offering' refers to the standard offering, or the lowest common denominator of the different possible offerings. The available options are added features or related services that can help differentiate the offering.

3.2. Benchmarking of the ERU offering[4]

Natural uranium and related front end products and services needed to make fuel assemblies and have them delivered to the reactors constitute, for the time being, the incumbent solution to fuel LWRs. For benchmarking RepU, a segment-by-segment comparison appears irrelevant, because its economics do not rely only on the comparison of front end services, such as conversion and enrichment or blending, against the price of the primary raw material, namely natural uranium. Instead, natural uranium and RepU are different in nature, and the two objects that are comparable are the end products, that is to say fuel assemblies (ENU fuel and ERU fuel) including their fissile material content.

Another reason not to compare RepU and natural uranium concentrate is that the RepU characteristics differ from those of natural uranium, making front end treatment and services characteristics for natural uranium not applicable to RepU. As a matter of facts, RepU has different isotopic characteristics than natural uranium which are somewhat exacerbated during the enrichment phase as even isotopes neighbouring the fissile ^{235}U isotope are also enriched.

Unlike metals used for their physical and mechanical properties and, therefore, being recycled as such (aluminium, copper, iron…), the fuelling capability of nuclear fuel assemblies lies in their fissile isotopes content and their burning in nuclear reactors implies a loss of 'quality'[5] as the fuel becomes used.

For the comparison to be valid, the fissile isotope content of the two fabricated fuels (from natural uranium and from RepU) must ensure the same in-core performance. That is achieved by the front end processing which must fill the gap between the fuel assembly fabricated with RepU and the incumbent ENU fuel assembly (e.g. over-enrichment in ^{235}U and/or dilution of even isotopes).

Marketing of aluminium substitutes

In the case of most commodities, the price of the substitute has to be compared to the market price of the commodity. In the case of recycled products or scraps, their market value is a published price, which incorporates a 'price spread', depending on the cost of processing the scraps. With sustainable development issues getting ground, dumping a used product will be more and more translated into monetary terms, as for example by the introduction of a tax. For the energy market one can think of the taxation on CO_2 emissions. A dumping tax might provide also some more impetus for the recycling of scraps.

A quick view at the aluminium market indicates that recycling relies on two main factors: economics and availability. Although in the case of aluminium the economics are undoubtedly in favour of recycling, there is no real market choice between primary aluminium coming from bauxite and recycled product, because the level of available scrap is much too low to cover a significant part of the market [4]. The challenge this industry is facing is a lack of available material to recycle, which is (as a paradox) not stimulated by demand. Demand for aluminium pushes prices up, which stimulates the mining industry and the resulting primary aluminium supply, but the dynamics of recycling follows other paths. As stated in one article on aluminium recycling, '…you cannot go out and plant more scrap trees or open a new scrap mine." [5].

4. Market segment and targeted customers step

As this paper tends to be rather general in presenting the value drivers for RepU, it will not define any potential 'best' customer for RepU but rather analyse the potential market and see how RepU has been presented to customers in the past.

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[4] This step of the marketing methodology applied says that a value proposition has to be benchmarked against a market leader, another technology, or an incumbent solution. A competitive benchmarking can also be a 'make or buy' analysis.

[5] That is to say a degradation of their fissile isotopes inventory.

4.1. Market segment

From a purely technical point of view, RepU is loadable into any reactor that burns uranium, be it enriched or not. But some limitations in the use of RepU can arise in certain countries due to restrictive back end policies including potential bans on using RepU as it relates to the closed fuel cycle. Nevertheless, the potential market for RepU assemblies is the the bulk of the world's nuclear fleet. RepU use is not a niche market; it is rather under-utilized.

Is RepU under-utilized because of a lack of raw material?

The answer is simply 'no'. The current RepU stocks are evaluated at 45 000 tonnes U, stemming from the French, British and Russian reprocessing plants. According to OECD/NEA [1], the natural uranium equivalent is 50 000 tonnes U, which indicates an average ^{235}U assay which is about 10% above that of natural uranium, representing a slight enrichment indeed. In addition, the existing reprocessing plants have the capability to add a potential flux of several thousands tonnes RepU per year. RepU is not lacking, it remains under-utilized.

Can this situation last? Taking into account that RepU availability allows to displace part of the demand to fuel reactors, the rational market answer should become 'no'. The present situation where natural uranium production is lagging behind the utilities' demand and is, therefore, pushing prices to levels which were unknown in the past appears unsustainable. While fissile materials that are still contained in the used fuel if recovered during reprocessing have the capability to fuel (as MOX and ERU) up to one fourth of the reactors' fleet, as has been achieved by a few operators, this is obviously not the case for the nuclear reactor park worldwide.

To draw a parallel with the uranium mining market, one can say that the 45 000 tonnes U accumulated to-date, with the potential yearly addition of several thousands tonnes, are resources rather than reserves. We know that we have and will continue to have RepU available as well as we know that the worldwide uranium resources already discovered (and to be discovered thanks to the growing exploration efforts) will be sufficient to sustain the nuclear renaissance. However, these resources have yet to be turned into reserves and readily marketable production.

Is RepU under-utilized because of excess supply of natural uranium? The answer is 'no' as present mine production is below the necessary quantities needed to quench the current market's thirst for nuclear fuel.

Is RepU under-utilized because it is part of the utilities' strategic stocks? This has certainly been true up to the early 2000s when the market was flooded with natural uranium concentrates. While the situation has recently changed, the real willingness for utilities to rely more on RepU has yet to materialize.

Is RepU under-utilized because the proper channels to market it are missing? This has certainly been the case until recently. The fact is that RepU - be it stored as uranyl nitrate, UO_3 or as U_3O_8 - cannot use all the channels available for natural uranium concentrates to fuel reactors. To have RepU in the form of fuel assemblies ready to be loaded into reactors requires several specific steps which are not yet available on a full commercial scale.

The fact is that the industry, due to lack of a sufficiently materialized demand, has failed to implement the proper mechanisms to make RepU able to fuel reactors.

4.2. Targeted customers step

Due to the specifics linked to the use of RepU as reactor fuel, targeted customers could be the reactors' operators which have entered the closed fuel cycle scheme or which are planning to do so. For such customers, trading-off management of RepU for its utilization as fuel in reactors is a natural outcome of their back end strategy.

However, there is no requirement for the production and the consumption of RepU to be strictly linked together. In particular, some utilities may not be willing to use RepU because of upfront engineering

costs or administrative limitations (licensing), thus making it available to other utilities which are already burning ERU fuel or which could be easily licensed to do so.

5. Identification and evaluation of value drivers step

What can be valued in the offering and how much is it valued?

Once the product, the market segment and the targeted customers have been defined, the value elements of the offering need to be identified and estimated by comparison to the reference offering. They classically fall into four categories:

- Points of parity: Both offerings provide the same performance of functionality;
- Points of contention: Supplier and customer disagree over the value of the element;
- Points of difference: Offering is clearly and demonstrably superior compared with the reference one; and
- Placeholders: Offering is different, but we cannot quantify the difference.

In Table 1 the tentative value drivers, the points of contention and the points of parity are the ones that can be the most easily valued.

Valuating these elements would, however, require having selected customers. In particular, the value analysis may be different whether a utility owns or does not own RepU inventories, or whether it has already recycled spent fuel or is at least planning to do so. A value element evaluation depending on the processing route is given in Table 2.

TABLE 1. VALUE ELEMENT CHECKLIST FOR A REPU OFFERING

Type of Value Element	**Value Elements of the RepU Offering compared to Reference Offering (ERU Fuel Assembly)**	**Is the Element relevant to Customer?**
Points of parity		
	Fuel assembly structure	Y
	Material and fuel assembly transport	Y/N
Points of contention		
	Yield of ERU assembly (expressed in kWh or Equivalent Full Power Days (EFPD))	Y
	Handling of RepU during its processing (e.g. cylinder cleaning)	Y/N
	Enrichment level of ERU	Y/N
	Core management	Y
	Licensing effort to introduce new fuel	Y
	Conversion and enrichment savings (for the blending route)	Y/N
Points of difference		
	Natural uranium savings	Y
	Predictability of fuel cost	Y/N
Placeholders		
	Indirect impact on U_3O_8 prices: relieves the buying pressure on the U_3O_8 marketplace	Y
	Reaffirmation of a back end strategy	Y/N
	Trend-setter in fuel management, ready to experience different type of fuel	Y
	Security of supply, management of strategic inventory of fissile material of the utility	Y/N

TABLE 2. VALUE ELEMENT EVALUATION DEPENDING ON THE PROCESSING ROUTE

Type of Value Element	**Traditional Route**	**Blending Route**
Point of contention	Must-have: a satisfactory performance level (i.e. comparable to Unat). *Ultimately, when it comes to delivering value to reactor operators, the measuring unit is the amount of electricity yielded by the fuel assembly. From that standpoint, RepU suffers from a 'built-in feature' (meaning even isotopes), which implies lower yield for a given enrichment*[6].	
Points of contention	Extra cost along the RepU fuel assembly supply chain: specific conversion, radiation protection measures at fuel fabrication stage	Blending subject to the availability of uranium enriched to a ^{235}U level above the commercial facilities' limits
Point of contention		Loss of SWUs
Point of contention		Limited RepU consumption
Point of contention	One time upfront costs (licensing and handling measures to implement) at least comparable to those related to the introduction of a new fuel management. Therefore, utilities that already have adapted their reactor to RepU loading can give a higher value to burning it than utilities that have only relied on natural uranium so far.	
Point of difference	For a utility having its used fuel reprocessed, RepU is readily available at no cost according to its reprocessing contract	
Point of parity		No core adaptation required. Very limited upfront costs

6. Building a value model

This step of the CVM methodology is simply a discussion about the different value elements (the pros and cons) which have been identified in Section 5.

Costs and price arguments

Although it is not commonly quantified, it seems to be really difficult to find a trade-off between the lower cost of RepU and its loss of fuel performance. Fuel performance is at the heart of the utilities' fuel management and the equivalence of performance between RepU fuel and ENU fuel is a 'must-have'. The cost of any performance degradation of the fuel translates into costs that are way higher than the cost of RepU processing.

With even less 'commodities' in the ERU fuel assembly than in the ENU fuel assembly, shifting to ERU fuel represents a switch from commodity to engineering. One is no longer dealing with a commodity the price of which is set by the market, but with a set of industrial products and services. However, this is based on the assumption that we set a fixed value for RepU (negative, zero, or positive), independent from the price of natural U_3O_8 (other commodity markets, such as aluminium,

[6] However, it does not necessarily mean that more SWUs would be required as RepU's average initial enrichment is above that of natural uranium (see Section 4.1.).

follow other rules and value of scraps, according to their value-in-use with reference to the primary aluminium price).

What would be the ideal price for RepU? As an ERU fuel assembly is a substitute to uranium, the pricing of RepU should in theory be linked to the market price of uranium, even though the costs are not related. Whenever ERU fuel is notably less expensive than ENU fuel, this should lead to exerting a downward pressure on ENU prices and an adjustment of prices. From a theoretical point of view, RepU would increase the elasticity between nuclear fuel demand and natural uranium offers.

Sustained high prices for natural uranium, leading to the cost of ENU fuel being greatly higher than ERU fuel, would lead RepU owners to reconsider the value of their stock and set for it a positive value. RepU inventories would turn from a liability into an asset.

Fuel cycle arguments and sustainable development

One of the major placeholders of RepU is the reaffirmation of a back end strategy. This belongs to back end related arguments. Such a value element can be included in a global sustainable development reasoning, aiming at reducing the overall quantities of spent fuel and a better use of the fissile material.

Other strategic elements in favour of RepU are the management of the fissile material inventories (e.g. uranium savings) and security of supply at a reasonable cost.

7. ‘Craft value proposition’ step

This last step of the CVM analysis aims at presenting to the potential customers a value proposition based on the value model defined in Section 6. We review hereafter how RepU has been viewed in the past, referring to past presentations from suppliers and/or utilities. The following points are the ones highlighted by authors/authoring organizations, with the upper points highlighted more frequently than the ones at the end of this list:

- Loss of performance of ERU fuel and difficulties in processing/handling due to even uranium isotopes;
- Industrial experience and maturity of the solutions to process RepU;
- Link to back end policies;
- Natural uranium savings;
- Negligible market share; and
- Investments needed in the industrial supply chain.

Many papers and presentations on RepU start in a classical way by describing the product, insisting on its characteristics, especially even isotopes. This unfortunately still conveys the message that ERU fuel is a low-quality fuel, in contrast to the maturity of the industrial solution for its processing, and its subsequent positioning in a global fuel cycle strategy.

This paper concludes by suggesting hereafter avenues worth exploring:

- ENU versus ERU represents a further switch from a commodity market to an ‘engineering’ market, where costs do not depend on the market value of a commodity, but rather on industrial cost. This should bring more stable prices for the utility and it allows the suppliers to escape the ‘commodity magnet’ (commoditization). However, two factors must me considered: upfront costs for building new facilities for processing RepU, and the fact that ERU is a substitute to ENU, the price of which should be related to. If RepU would readily be available and plentiful, we should even have a market price for RepU!
- In order to ensure equivalent product quality, utilities and suppliers should investigate ways to lift the 5% limit of the ^{235}U enrichment. However, the 5% enrichment limit does not hamper the blending route as much as the traditional route (physical re-enrichment).

- In the same vein, the use of ERU in first cores could be investigated, as the enrichment requirement is lower than for equilibrium reloads.
- The market would benefit from a sharing of experience on the use of RepU and the assessment of upfront engineering and licensing effort for those utilities which are not acquainted with RepU. The same would apply to obligations on fissile material.

Couldn't the work achieved during the IAEA's Technical Meeting on RepU held in Vienna late in August 2007 and the drafting of the following technical document be leveraged into a RepU users' 'fan club'?

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Impact of market conditions on the economics of RepU utilization

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Abstract. In a topical paper presented at the Technical Meeting on 'Fissile Material Management Strategies for Sustainable Nuclear Energy', Vienna, 12-15 September 2005 [1], sensitivity of fuel costs to the quality of reprocessed uranium (RepU) was illustrated for centrifuge-enriched RepU. The economics of RepU was treated very superficially, since the purpose was only to indicate how much the value of RepU depends on the burnup of the spent fuel from which the RepU was recovered. Furthermore, the prices in the front end of the fuel cycle (U_3O_8, conversion, enrichment and fuel fabrication) were taken at the market levels of 2004-2005. Since then, the price of natural uranium (Unat) has increased by a factor 9 and the enrichment price by a factor 1.7, and some believe that those prices might continue to escalate further beyond the normal inflation rate of goods. In this context, this paper analyses in more detail the cost of enriched reprocessed uranium (ERU) fuel, as a function of the RepU quality, market prices of the fuel cycle front end and enrichment technology. No attempt is made to be exhaustive. It is only a case study based on extreme price assumptions. The results are one input to a decision on whether to utilize available RepU in the short term to benefit from attractive enrichment conditions or to store it as strategic reserve to be used later. Besides economic evaluations, other factors are also to be taken into consideration: perspectives of future burnup increases, evolution of the regulatory limitations, political decision to phase-out nuclear energy, etc.

Introduction

Starting in 1976, when the price of natural uranium (Unat) was high, reprocessed uranium (RepU) recovered from reprocessing Magnox fuel was re-enriched and fabricated into fuel for the British Advanced Gas-cooled Reactors (AGR). Over 15 000 t Magnox RepU was recycled to produce over 1500 tU of enriched reprocessed uranium (ERU) fuel for AGRs. The recycle ceased in 1996 as it became economically unattractive due to a combination of factors, such as low ^{235}U content of Magnox RepU (with increasing discharge burnups) and falling natural uranium prices [1].

Utilization of RepU in Light Water Reactors (LWR) began in the German Pressurized Water Reactor (PWR) Obrigheim in 1983, which was followed in the late 1980s by Japan, France and Belgium.

Except for light water-cooled, graphite moderated reactors (RBMK), the 1985-2004 price levels of Unat prevented RepU to be competitive. However, if not utilized forever, RepU constitutes a liability consisting in the costs of conditioning, interim storage and final disposal as a waste. As a result, in countries with political uncertainty about the future of nuclear power generation, such as Belgium, Switzerland, Germany and The Netherlands, the utilities did recycle their RepU in the LWRs.

Countries with a long-term policy of nuclear power generation, like France and Japan, store their RepU as a fissile material reserve. Recycling some of it as ERU is only applied on a reduced scale to insure availability and maintenance of the technology. Since many years, Electricité de France (EDF) fuels two 900 MW(e) reactor units at Cruas predominantly with ERU reloads. Most of EDF's RepU is converted to oxide and kept as a strategic inventory, which amounted to 10 000 t U in 2006, of which, under the current licensing conditions[1], 7000 t could be enriched and recycled as ERU, equivalent to

[1] Explained in Section 3

one year fuel requirement of the French utility [2]. However, as Unat prices rise, EDF is seriously considering to increase the quantity of ERU fuel in the reloads of their reactors.

Without aiming at being exhaustive, this paper will provide some insight on the influence of front-end market prices on the competitiveness of ERU. This case study will be restricted to one PWR fuel example.

Front end market prices

In the cost comparison, we will assume that the RepU resource is cost-free, i.e. it has no commercial value. This assumption could be debated. On the one hand, one could consider that RepU has to bear part of the extra cost of the reprocessing option over the once-through fuel cycle option. If the economic evaluation shows the ERU fuel to be less (or more) expensive than enriched natural uranium (ENU) fuel, it will indicate a positive (or negative) value for the RepU and how much it can contribute to reduce (or increase) the cost differential of the two back-end options. On the other end, if reprocessing is chosen as a policy irrespective of cost considerations, RepU not utilized as a resource would need to be disposed of as waste. Therefore, avoided waste disposal cost by recycling RepU as ERU should be booked as a bonus.

The cost constituents of a fresh ERU fuel assembly are:

- Conversion of U_3O_8 into UF_6 (e.g. in France) or of UO_3 into UF_6 (e.g. in the United Kingdom), U_3O_8 and UO_3 being the two interim storage compounds of RepU. We will assume that, per kgU to be converted, the price is six time higher for RepU than for Unat, to take into account the extra costs of cleaning the storage/transport cylinders, of conditioning and disposing the highly radioactive waste[2], of separating the conversion of RepU and Unat to avoid cross-contamination and of operating in smaller batches (and making uniform the different isotopic compositions of RepU deliveries, while the isotopic composition of Unat is originally uniform).
- Enrichment into UF_6 of equivalent reactivity. We will assume that, per SWU, the price is 10% higher for RepU than for Unat, to take into account the extra costs of devoting specific cascades to ERU. Additional radioactive waste is a very minor problem in this case, since the strong gamma emitting daughter products of ^{232}U are retained as deposits in the UF_6 cylinders and the enrichment operation is short compared to the decay time to produce a new generation of decay products.
- Fabrication into an ERU fuel assembly for a PWR. We will assume that the fabrication price, which includes fuel engineering, hardware, etc. is 20% higher for ERU fuel than for ENU fuel, to take into account the extra costs of specific waste arisings, investments in shielding of the ERU fuel fabrication line, additional cleaning of the fabrication line to avoid contamination of the next ENU fabrication campaign, etc.

TABLE 1. MARKET PRICES TAKEN FOR CALCULATION OF ENU FUEL COST

Item	Unit	Past (1990s)	Current spot	References
U_3O_8	USD/lb U_3O_8	10	130	[3] and [4]
Conversion	USD/kg U	5	12	[3] and [4]
Enrichment	USD/SWU	70	140	[3] and [4]
Fabrication in Asia	USD/kg U	670	330	[5]
Fabrication in Europe	USD/kg U	540	290	[5]
Fabrication in USA	USD/kg U	330	220	[5]

[2] In the conversion process, the RepU is cleaned from the strong gamma emitting daughter products of ^{232}U which do not form volatile fluorides [1].

Only two sets of market prices will be considered (Table 1), one being illustrative of the past (in the 1990s) and one being representative of present spot market[3], which could (but might not) be representative of future trends for long-term contracts.

As the exchange rates have fluctuated over a wide range within this period[4], the price data have been converted in USD at the exchange rates applicable at the time considered.

Centrifuge enrichment

The enrichment requirements are greatly influenced by the discharge burnup of the fuel from which the RepU is recovered. For this case study, RepU is assumed to originate from spent fuel initially enriched at 3.5% ^{235}U, typical of European PWR fuel discharged at 38-42 GW•d/t HM in the mid-1990s, to have been stored 10 years and to be re-enriched and fabricated into ERU fuel assemblies equivalent to 4.4% ^{235}U ENU, typical of mid-2000s European PWR fuel designed for a discharge burnup around 50 GW•d/t HM. Table 2 provides the isotopic composition of those fuels, as well as the enrichment requirements. The tails assay of enrichment is supposed to be 0.3% ^{235}U.

TABLE 2. FEED AND ENRICHMENT REQUIREMENTS FOR FABRICATION OF 1KG ENU AND ERU FUEL, RESPECTIVELY, WITH ENRICHMENT OF 4.4% ^{235}U EQUIVALENT [1)], AS FUNCTION OF SOURCE MATERIAL

Source Material				Product		
Type	**Burnup (GW•d/t HM)**	**^{235}U (%)**	**^{236}U (%)**	**^{235}U (%)**	**Requirements**	
					Feed (kg U)	**Enrichment (SWU)**
Unat	0	0.71	negligible	4.40	10.0	6.0
RepU	36	0.84	0.45	5.00	8.7	6.3
RepU	40	0.69	0.47	5.18	12.5	7.7
RepU	44	0.56	0.48	5.45	19.7	9.6

[1)] Enrichment of RepU in centrifuges.

The current licensing limit of 5% ^{235}U for all front-end industrial infrastructures, applicable also to ERU, prohibits the possibility of recycling RepU originating from spent fuel discharged at burnups higher than 36 GW•d/t HM, in the examples illustrated Table 2. However, if the use of ERU becomes more common in the future, there is little doubt[5] that the poisoning effect will be accounted for and ERU enrichments of 6% ^{235}U or more (depending on the proven ^{236}U content) will be licensable as considered equivalent to ENU with an enrichment of 5% ^{235}U.

Tables 3 and 4 provide the cost results of the four fuels defined in Table 2, for each of the two sets of price conditions given in Table 1.

According to Table 3, ERU fuel is not competitive under the past market price conditions given in Table 1. Only RepU issued from lower burnup spent fuel can be recycled at a reasonable cost penalty. It was the case of the RepU available up to the mid-1990s.

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[3] Most of these 13x and 2x price increases of respectively U_3O_8 and enrichment are quite recent. Since 2000, the increases have been respectively 9x and 1.7x.

[4] For instance, 1 euro was as low as USD 0.70 twenty years ago and is currently USD 1.40.

[5] This believe is based on what happened in the past, when licensing limits based on fresh fuel enrichment were applicable to spent fuel, while currently burnup credit has entered the regulatory arsenal.

TABLE 3. COST (USD/kg U) OF ENU AND ERU FUEL AT PAST MARKET PRICES[1)]

Item / Total	Product			
	ENU 4.40% ^{235}U	**ERU 5.00% ^{235}U**	**ERU 5.18% ^{235}U**	**ERU 5.45% ^{235}U**
U_3O_8	260	-	-	-
Conversion into UF_6	50	260	375	590
Enrichment	420	485	590	740
Fabrication in Asia	670	740	740	740
Fabrication in Europe	540	590	590	590
Fabrication in USA	330	360	360	360
Fuel assembly cost in Asia	1400	1480	1705	2070
Fuel assembly cost in Europe	1270	1340	1560	1920
Fuel assembly cost in USA	1060	1110	1330	1690

1) All figures have been rounded to improve readability.

TABLE 4. COST (USD/KGU) OF ENU AND ERU FUEL AT CURRENT SPOT MARKET PRICES[1)]

Item / Total	Product			
	ENU 4.40% ^{235}U	**ERU 5.00% ^{235}U**	**ERU 5.18% ^{235}U**	**ERU 5.45% ^{235}U**
U_3O_8	3380	-	-	-
Conversion into UF_6	120	630	900	1420
Enrichment	840	970	1190	1480
Fabrication in Asia	330	395	395	395
Fabrication in Europe	290	350	350	350
Fabrication in USA	220	260	260	260
Fuel assembly cost in Asia	4670	1990	2480	3290
Fuel assembly cost in Europe	4630	1940	2430	3240
Fuel assembly cost in USA	4560	1860	2350	3160

1) All figures have been rounded to improve readability.

However, according to Table 4, for current market prices given in Table 1, ERU becomes very attractive[6]. But for licensing reasons as indicated above, it can currently only be implemented for RepU originating from lower burnup spent fuels, preventing part of the RepU stockpile to be recycled now by centrifuge re-enrichment.

The major influence in this reversal of ERU's competitiveness comes from the price of Unat. Figure 1 plots the results of Tables 3 and 4 for European conditions as a function of the price of Unat. It shows that the RepU types illustrated in this paper would be economically attractive to be recycled when the price of Unat exceeds USD 20-50/lb U_3O_8, depending on the RepU's isotopic quality. It is within the price range predicted[7] for after 2010.

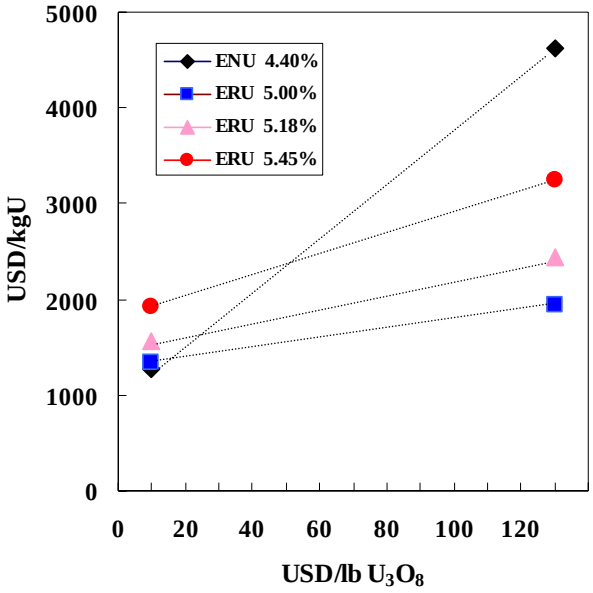

FIG. 1. Fresh fuel assembly costs plotted as function of U_3O_8 prices (European market conditions; enrichment of RepU in centrifuges).

The 5% ^{235}U limit, to which almost all the fuel industry infrastructure is designed and licensed for, is currently applicable also to ERU. For most RepU issued from spent fuel discharged over the past ten years, as burnup has increased during this period to 50 GW•d/t HM, it would mean that ERU fuel limited to 5% ^{235}U could not be made equivalent to standard ENU fuel. The resulting lower discharge burnup capability of such ERU leads to a fuel cycle cost penalty, much bigger than the fuel cost penalty or advantage illustrated in this section.

Enrichment by blending with MEU or HEU

The higher enrichment of ERU fuel required to meet equivalence to ENU fuel is due to the increase in the ^{236}U content by enriching the RepU in centrifuges. The ^{236}U content of ERU can be mitigated by adding to the RepU a blendstock of HEU, MEU or even lower enriched uranium, rather than enriching the material by centrifuges. Table 5 compares the ERU compositions for the three fuel cases illustrated in Table 2, i.e. RepU issued from spent fuel originally 3.5% ^{235}U enriched and irradiated to 36-44 GW•d/t HM, stored 10 years and re-enriched to be equivalent to ENU fuel with an enrichment of 4.4%

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6 The ENU fuel assembly cost could be reduced, e.g. from 4630 to 4210 for European conditions, by adopting 0.2% tail assay instead of 0.3%. But even so, ERU remains attractive.

7 The longer-term price level is a matter of speculation, with predictions ranging between USD 30 and 70/llb U_3O_8 [6] in the next decade, when flooding at several uranium mines will be solved and new mines will start operation. The most likely price range is USD 35-40/lb during that period.

^{235}U. The example given in Table 5 assumes that MEU is the blendstock used to enrich the RepU feed and that this blendstock does not contain ^{236}U, i.e. it is not issued from reprocessing[8].

The resulting ERU isotopic composition is almost independent of the isotopic quality of the RepU feed and is well within the current 5% ^{235}U licensing limit. It could therefore be applied currently to almost any RepU.

However, there is no economic incentive (Tables 6 and 7) to use this ERU rather than ENU. In these tables, the U_3O_8 and SWU prices of the MEU fraction in each kg ERU have been taken equal to the prices applied for the ENU, which means that the MEU blendstock is assumed to be produced for the purpose of enriching RepU and is not from existing excess MEU stocks that could be available at discount price.

TABLE 5. INFLUENCE OF ENRICHMENT PROCESS ON ERU FUEL COMPOSITION

Source Material				**Product**			
Type	**Burnup (GW•d/t HM)**	**^{235}U (%)**	**^{236}U (%)**	**Enrichment Process**			
				Centrifuge		**Blending[1)]**	
				^{235}U (%)	**^{236}U (%)**	**^{235}U (%)**	**^{236}U (%)**
Unat	0	0.71	-	4.40	-	4.40	-
RepU	36	0.84	0.45	5.00	1.75	4.49	0.36
RepU	40	0.69	0.47	5.18	2.31	4.49	0.38
RepU	44	0.56	0.48	5.45	4.67	4.50	0.38

[1)] Blending with unirradiated 20% enriched uranium.

The cost difference between the ERU fuel with 5.18% ^{235}U produced by centrifuges and the ERU fuel with 4.49% ^{235}U produced by blending seems small in Table 6. But the comparison should take into account that all the RepU feed is incorporated in ERU fuel produced by blending, while, by centrifuge enrichment, a lot[9] of depleted RepU is generated, the isotopic composition of which might tag it as waste (and no more as strategic fissile material stock). The cost of a reserve fund to be constituted for waste disposal would add to the fuel assembly cost of ERU fuel produced with centrifuges.

Such considerations explain why, in 1989, 16 t RepU from spent (stainless steel clad) fuel of the 310 MW(e) Chooz-A PWR at a residual enrichment of 1.9% 235U was blended with 4.9% ENU, to manufacture ERU fuel with an enrichment of 3.85% ^{235}U which was loaded into two Belgian PWRs, the 1000 MW(e) Doel-4 and the 900 MW(e) Tihange-2 reactors [8].

Table 7 indicates that this blending solution with unirradiated enriched blendstock becomes prohibitively expensive when the prices of yellow cake and of enrichment increase. Accordingly, the use of freshly produced MEU as blendstock is obviously not a solution for the future. Given the cost impact of the blendstock material, the optimum is probably at a blendstock enrichment lower than 20% ^{235}U. However, it should be noted that using MEU with an enrichment of 20% ^{235}U generates already 1.25 kg ERU fuel for each kg RepU recycled. Reducing the enrichment of the blendstock would increase the amount of ERU fuel to be loaded and enough reactors should be available.

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8 It means MEU produced from downblending unirradiated HEU or from enriching Unat. The inventory of unirradiated HEU end 2003 [7] is approximately 1700 t (of which over 1200 t in military stocks and over 400 t declared excess over military needs) enough to re-enrich 40 000 t RepU.

9 e.g. 11.5 kg depleted RepU for each kg of 5.18% ERU fuel fabricated.

TABLE 6. COST (USD/KG U) AT PAST MARKET PRICES OF ENU FUEL AND OF ERU FUEL FABRICATED FROM REPU ORIGINATIONG FROM SPENT FUEL WITH BURNUP OF 40 GW•d/t HM[1)]

Item / Total	**ENU 4.40% ^{235}U**	**ERU 5.18% ^{235}U**	**ERU 4.49% ^{235}U**
	Enrichment Process	**Enrichment Process**	
	Centrifuge	**Centrifuge**	**Blending**
U_3O_8	260	-	200
Conversion of Unat into UF_6	50	-	39
Conversion of RepU into UF_6	-	375	24
Enrichment by centrifuge	420	590	640
Enrichment by blending	-	-	30
Fabrication in Asia	670	740	740
Fabrication in Europe	540	590	590
Fabrication in USA	330	360	360
Fuel assembly cost in Asia	1400	1705	1680
Fuel assembly cost in Europe	1270	1560	1530
Fuel assembly cost in USA	1060	1330	1300

[1)] All figures in this table have been rounded to improve readability.

TABLE 7. COST (USD/KG U) AT *CURRENT* SPOT MARKET PRICES OF ENU FUEL AND OF ERU FUEL FABRICATED FROM REPU ORIGINATIONG FROM SPENT FUEL WITH BURNUP OF 40 GW•d/t HM[1)]

Item / Total	**ENU 4.40% ^{235}U**	**ERU 5.18% ^{235}U**	**ERU 4.49% ^{235}U**
	Enrichment Process	**Enrichment Process**	
	Centrifuge	**Centrifuge**	**Blending**
U_3O_8	3380	-	2585
Conversion of Unat into UF_6	120	-	92
Conversion of RepU into UF_6	-	900	58
Enrichment by centrifuge	840	1190	6410
Enrichment by blending	-	-	72
Fabrication in Asia	330	395	395
Fabrication in Europe	290	350	350
Fabrication in USA	220	260	260
Fuel assembly cost in Asia	4670	2480	9610
Fuel assembly cost in Europe	4630	2430	9570
Fuel assembly cost in USA	4560	2350	9480

[1)] All figures in this table have been rounded to improve readability.

Enrichment by blending with reprocessed MEU

Russia started using ERU by fuelling an RBMK-1000 in 1980 and, by 1983, had expanded this use to the four RBMK-1000 units at Sosnovy Bor [8]. ERU utilization is interesting in this reactor type because the poisoning effect of ^{236}U is much lower in the RBMKs' neutron spectrum (as is also the case for CANDUs) than in the neutron spectra of LWRs. The over-enrichment compensation factor in ERU is only 5% $^{235}U/^{236}U$ for RBMKs, against 26-34% for LWRs and 25% for water-cooled and water-moderated reactors (WWER) [1].

With the residual enrichment in spent RBMK fuel being too low for reprocessing to be justified, the RepU feed is issued from the reprocessing of WWER-440 spent fuel, which has an average discharge isotopic composition of 0.95-1.0% ^{235}U and 0.3% ^{236}U. Besides WWER-440 fuel, the RT-1 plant at the Production Association 'Mayak' in the Urals (Chelyabinsk region)) also reprocesses spent fuel from research reactors, from naval reactors (ice-breakers and submarines) and from the BN-600 Fast Breeder Reactor (FBR), with residual enrichments respectively 70, 17 and 20% ^{235}U. From these RepU streams, one of the uranium finishing lines of RT-1 produces a MEU blendstock at 14-17% ^{235}U and 1.5% ^{236}U, which is used to enrich the WWER RepU feed to the enrichment of 2.6-2.8% ^{235}U needed for RBMK fuel ([1] and [8]).

Since 1990, the 11 Russian RBMK-1000 units are routinely refuelled with ERU up to 50% of the core. This wider use of ERU was possible by using not only WWER RepU but also LWR RepU 'tails' generated by re-enrichment contracts for German, Swiss, Swedish and Dutch utilities, which specify that material balance and price calculations are based on equivalent centrifuge enrichment conditions. Besides generating additional feed to produce more ERU fuel for RBMK-1000 plants, this commercial deal presents advantages for both the Russian service supplier and the foreign customers [1].

For the three RepU fuel cases defined in Table 2 and a blendstock containing 17% 235U and 1.5% 236U, Table 8 gives the composition of produced ERU fuel. It has almost the same advantages as ERU fuel from blending with unirradiated MEU. In particular, the enrichment of the ERU is well below 5.0% ^{235}U.

Table 9 provides the contractual input data for material balance and price calculations, assuming a tails assay of 0.3% 235U, as in Section 3. It shows that, for each kg ERU returned to the LWR customer, 6.9 to 15.5 kg RepU (depending on the isotopic quality of the RepU) is generated for making ERU fuel for RBMKs. This additional source of RepU is now welcome [1].

Tables 10 and 11 show the resulting cost of ERU fuel for each of the two sets of price conditions defined in Table 1.

TABLE 8. INFLUENCE OF ENRICHMENT PROCESS ON ERU FUEL COMPOSITION

Source Material				**Product**			
				Enrichment Process			
				Centrifuge		**Blending[1)]**	
Type	**Burnup (GW•d/t HM)**	**^{235}U (%)**	**^{236}U (%)**	**^{235}U (%)**	**^{236}U (%)**	**^{235}U (%)**	**^{236}U (%)**
Unat	0	0.71	-	4.40	-	4.40	-
RepU	36	0.84	0.45	5.00	1.75	4.57	0.69
RepU	40	0.69	0.47	5.18	2.31	4.58	0.72
RepU	44	0.56	0.48	5.45	4.67	4.58	0.73

[1)] Blending of RepU with MEU at 17% ^{235}U and 1.5% ^{236}U.

TABLE 9. SPECIFICATION OF SOURCE MATERIAL AND FEED AND ENRICHMENT REQUIREMENTS FOR FABRICATION OF 1KG ENU AND ERU FUEL, RESPECTIVELY, WITH ENRICHMENT OF 4.4% ^{235}U EQUIVALENT [1)2)]

Source Material				Product		
Type	Burnup (GW•d/t HM)	^{235}U (%)	^{236}U (%)	^{235}U (%)	Requirements	
					Feed (kg U)	Enrichment (SWU)
Unat	0	0.71	negligible	4.40	10.0	6.0
RepU	36	0.84	0.45	4.57	7.9	5.5
RepU	40	0.69	0.47	4.58	11.0	6.5
RepU	44	0.56	0.48	4.58	16.5	7.7

1) Enrichment of RepU by blending with MEU.
2) Input data for material balance and price of ERU fuel defined in Table 8.

TABLE 10. COST (USD/KGU) OF ERU FUEL AT PAST MARKET PRICES[1)2)]

Item / Total	Source Material			
	Unat	RepU 36 GW•d/t	RepU 40 GW•d/t	RepU 44 GW•d/t
	Product			
	ENU 4.40% ^{235}U	ERU 4.57% ^{235}U	ERU 4.58% ^{235}U	ERU 4.58% ^{235}U
U_3O_8	260	-	-	-
Conversion into UF_6	50	240	330	495
Enrichment	420	420	500	590
Fabrication in Asia	670	740	740	740
Fabrication in Europe	540	590	590	590
Fabrication in USA	330	360	360	360
Fuel assembly cost in Asia	1400	1400	1570	1825
Fuel assembly cost in Europe	1270	1255	1425	1680
Fuel assembly cost in USA	1060	1020	1190	1450

1) All figures have been rounded to improve readability.
2) Blending of RepU with MEU at 17% ^{235}U and 1.5% ^{236}U.

Under the past market price conditions (Table 10), ERU fuel was competitive only for RepU issued from lower burnup spent fuel, but RepU issued from spent fuel with a discharge burnup of 40 GW•d/t HM can be recycled at a reasonable cost penalty. Together with meeting the 5% enrichment limitation and the advantageous deal offered by TVEL[10], it explains why this re-enrichment option was qualified by Siemens in 1995 and became the sole option used for an increasing number of German and Swiss utilities since 1997 and of Swedish and Dutch utilities thereafter [8].

[10] For TVEL, this deal produces additional RepU feed needed to compensate for the then reducing VVER RepU feed [8] due to discontinuation of reprocessing spent fuel from the WWERs located outside Russia.

For the same reason as outlined in Section 3, ERU fuel is economically very attractive under the current spot market price conditions (Table 11). The major influence in this improvement of the ERU fuel's competitiveness comes from the price of Unat. Figure 2 plots the results of Tables 10 and 11 for European conditions as a function of the price of Unat. It shows that the RepU types illustrated in this paper would be economically attractive to recycle when the price of Unat exceeds USD 10-35/lb U_3O_8, (depending on the isotopic quality of the RepU), meaning for any price condition within the price range predicted for after 2010 as mentioned in footnote 7 (Section 3). However, this option for recycling RepU can not become of universal use, the production of reprocessed MEU being limited and diminishing even in the longer term [1]. When demand will exceed availability of reprocessed MEU, the commercial conditions will undoubtedly be adapted and this option will probably become economically equivalent to centrifuge enrichment described in Section 3.

TABLE 11. COST (USD/KGU) OF ERU FUEL AT *CURRENT SPOT* MARKET PRICES[1)2)]

Item / Total	Source Material			
	Unat	**RepU 36 GW•d/t**	**RepU 40 GW•d/t**	**RepU 44 GW•d/t**
	Product			
	ENU 4.40% ^{235}U	**ERU 4.57% ^{235}U**	**ERU 4.58% ^{235}U**	**ERU 4.58% ^{235}U**
U_3O_8	3380	-	-	-
Conversion into UF_6	120	570	790	1190
Enrichment	840	850	1000	1190
Fabrication in Asia	330	395	395	395
Fabrication in Europe	290	350	350	350
Fabrication in USA	220	260	260	260
Fuel assembly cost in Asia	4670	1810	2188	2770
Fuel assembly cost in Europe	4630	1420	2141	2720
Fuel assembly cost in USA	4560	1680	2057	2640

[1)] All figures have been rounded to improve readability.
[2)] Blending of RepU with MEU at 17% ^{235}U and 1.5% ^{236}U.

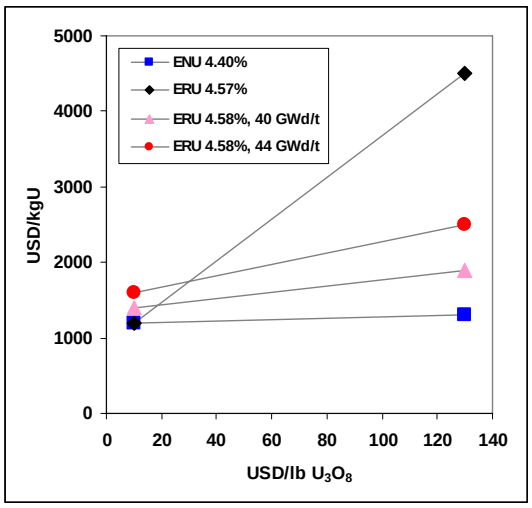

FIG. 2. Fresh fuel assembly costs plotted as function of U_3O_8 prices(European market conditions; blending of RepU with MEU at 17% ^{235}U and 1.5% ^{236}U).

Conclusions

The data generated have no absolute value, since this paper does not aim at being exhaustive, but only at showing sensitivity to market prices. It takes one case: an ERU fuel equivalent to 4.4% enriched ENU, to be manufactured from RepU issued from spent fuel discharged at three different burnups. The three enrichment processes used up to now are considered: centrifuge, blending with unirradiated enriched uranium and blending with MEU gained from reprocessing. No attempt has been made to optimize the economics by the adjusting tails assay, the enrichment of the enriched U blendstock, etc.

For each kg RepU being recycled:

- centrifuge enrichment generates 0.11 to 0.05 kg ERU and 0.89 to 0.95 kg depleted RepU, hardly to be considered any longer as a strategic fissile reserve;
- blending with unirradiated MEU generates 1.2 to 1.3 kg ERU (the NPP system must be able to absorb this increase fuel quantity) and 9 to 10 kg U tails, usually qualified as strategic fissile reserve;
- blending with reprocessed MEU generates 0.16 to 0.09 kg ERU and 0.9 kg original RepU, directly usable as RepU feed to manufacture RBMK (or CANDU) ERU fuel.

ERU from blending with unirradiated enriched uranium was competitive in the past, but is not competitive any longer and will continue to be even more expensive in the future. With the two other RepU enrichment options, ERU is currently less expensive than ENU and this competitiveness will increase in the future, when the price of Unat will increase. However, centrifuge enrichment can not be applied to RepU issued from higher burnup spent fuel, since the current 5% ^{235}U limit is exceeded.

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ABBREVATIONS

ADU	Ammonium di-uranate
AFD	Axial heat flux distribution
AGR	Advanced Gas-cooled Reactor
AHWR	Advanced heavy water reactor
ALARA	As low as reasonably achievable
ASTM	American Society for Testing and Materials
BOC	Beginning of cycle
BWR	Boiling water reactor
CANFLEX	CANDU FLEXible fuelling
CANDU	CANadian deuterium-uranium reactor
CCP	Critical channel power
CSI	Criticality safety index
DAC	Derived air concentration
DU	Depleted uranium
DUPIC	Direct use of spent PWR fuel In CANDUs
ECC	Emergency core cooling
EFPD	Equivalent full power day
ENU	Enriched natural uranium
EOC	End of cycle
ERU	Enriched reprocessed uranium
EUP	Enriched uranium product
FBR	Fast breeder reactor
FEA	Finite element analysis
FP	Fission product
GCR	Gas-cooled reactor
HEPA	High efficiency particulate airfilter
HEU	Highly enriched uranium

HLW	High level waste
HWR	Heavy water reactor
ICFM	In core fuel management
ILW	Intermediate level waste
INB	Installation Nucleaire de Base
IR	Inferred uranium resources
ISO	International standard organization
LEU	Low enriched uranium
LOCA	Loss-of-coolant accident
LWR	Light water reactor
MBP	Maximum bundle power
MCP	Maximum channel power
MDU	Magnox depleted uranium
MOX	Mixed (Uranium-Plutonium) oxide
MTC	Moderator temperature coefficient
NCT	Normal Conditions of Transport
NKSP	Nuclear key safety parameters
PDSR	Package design safety report
PHWR	Pressurized heavy water reactor
PUREX	Plutonium and Uranium Recovery by extraction
PWR	Pressurized water reactor
RAR	Reasonably assured resources
RBMK	Light water-cooled, graphite-moderated reactor
RepU	Reprocessed uranium
RFD	Radial heat flux distribution
RPP	Radiological protection programme
SEU	Slightly enriched uranium
SNF	Spent nuclear fuel

SWU	Separative work unit
SRU	Scrap recovery unit
Unat	Natural uranium
UNH	Uranyl nitrate hexahydrate
UOC	Uranium oxide concentrate
UOx	Uranium oxide
WWER	Water-cooled and water-moderated reactor

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